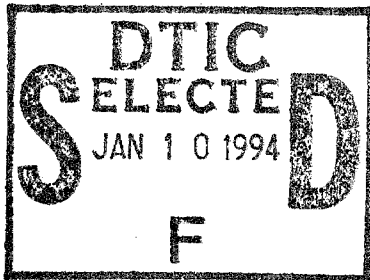


# **Evaluation of a New Laboratory Acoustic Doppler Velocimeter**



**A Major Report**

**by**

**Gary Neil Underwood**

**Submitted in partial fulfillment  
of the requirements for the degree of**

**MASTER OF ENGINEERING**

**December 1994**

**This document has been approved  
for public release and sale; its  
distribution is unlimited.**

**Major Subject: Ocean Engineering**

**19950105 033**

# Evaluation of a New Laboratory Acoustic Doppler Velocimeter

A Major Report

by

Gary Neil Underwood

Submitted in partial fulfillment  
of the requirements for the degree of

MASTER OF ENGINEERING

December 1994

REPRODUCTION OF THIS DOCUMENT IS UNLAWFUL

Major Subject: Ocean Engineering

Accession For	
NTIS CRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By <i>form 50</i>	
Distribution /	
Availability Codes	
Dist	Avail and/or Special
<i>A-1</i>	

## ABSTRACT

A small, rugged and relatively inexpensive velocity meter has been developed to measure uniform and oscillatory water flows in laboratory facilities. The Acoustic Doppler Velocimeter (ADV-1) is capable of measuring three-dimensional velocities. The ADV-1 measures velocities from 0 to 2.5 m/s at a sampling rate of up to 25 Hz. The measurements are made in a sampling volume located 5 cm in front of the probe. Since this instrument is new, the objective is to compare the ADV-1 with other laboratory current meters and prepare operational guidelines for the ADV-1 system. Three-dimensional velocities are measured in a wave tank with the ADV-1 horizontal velocity average 0.9 cm/s higher than the laser Doppler anemometer (LDA) and the ADV-1 vertical velocity average 0.93 cm/s lower than the LDA. A horizontal velocity profile is measured in a wave flume by the ADV-1 and a pitot tube, and the instruments differ by 3.5 %. Measuring velocity profiles around a stationary cylinder with the ADV-1 in the wave flume was highly successful, showing the ability of this instrument to measure velocities near structures in future laboratory research. The ADV-1 is portable and can be used for extended periods without recalibration.

## ACKNOWLEDGMENTS

I would like to thank my committee members, Dr. Robert E. Randall, Dr. Billy L. Edge, and Dr. Aubrey Anderson. Their assistance and guidance throughout my graduate education is greatly appreciated. A special thanks to Dr. Randall for his encouragement and support during the many hours of experimentation. Thanks are also expressed to Tony Spell for his assistance with the laser Doppler anemometer and Jun Zou for his assistance with the pitot tube system.

## TABLE OF CONTENTS

	Page
ABSTRACT.....	ii
ACKNOWLEDGMENTS.....	iii
TABLE OF CONTENTS.....	iv
LIST OF FIGURES .....	vi
LIST OF TABLES.....	ix
 CHAPTER	
1 INTRODUCTION.....	1
Background .....	1
Objectives .....	2
2 EQUIPMENT AND FACILITIES .....	2
Wave Tank.....	3
Wave Flume.....	4
Acoustic Doppler Velocimeter (ADV-1) .....	5
Laser Doppler Anemometer (LDA) .....	9
Wave gauge .....	10
Pitot Tube.....	11
3 EXPERIMENTAL PROCEDURES.....	12
Calibration of ADV-1.....	12
Comparison of ADV-1 with a Pitot Tube .....	12
Comparison of ADV-1 with the LDA.....	13
Flow Field Around a Cylinder.....	15
4 RESULTS.....	17
Calibration of ADV-1.....	17
ADV-1 and a Pitot Tube Comparison.....	17
ADV-1 and LDA Comparison.....	22
Velocity Profiles Around a Cylinder .....	36
5 CONCLUSIONS .....	43

	Page
REFERENCES .....	46
APPENDICES .....	47
1. ADV-1 Operational Manual .....	47
2. Suggested Mounting Device .....	54

## LIST OF FIGURES

FIGURE		Page
1	Schematic of laboratory wave tank and instrumentation.	3
2	Schematic of laboratory Variable Slope Wave Flume.	4
3	The ADV-1 system.	5
4	The ADV-1 probe.	6
5	The ADV-1 measurement geometry.	6
6	Various probe configurations.	8
7	Calibration of the ADV-1 using a tow carriage on a wave tank.	18
8	ADV-1 and pitot tube horizontal velocity profiles in the center of the flume.	19
9	ADV-1 and pitot tube horizontal velocity profiles near the wall of the flume.	20
10	Velocity profile at center of flume 0.84 m (2.77 ft) wide for a flow 0.18 m (0.59 ft) deep.	21
11	A plot of the Vanoni method versus experimental velocity profiles in the center of the flume.	21
12	Horizontal velocity of a 0.85 s period wave with height of 6.2 cm, 11 cm below SWL from test 1.	23
13	Wave elevation for the 6.2 cm wave height, 0.85 s period wave.	23
14	Horizontal velocity of a 0.85 s period wave with a height of 8.5 cm at a depth of 11 cm from test 2.	24
15	Horizontal velocity of a 0.85 s period wave with a height of 10 cm at a depth of 11 cm.	24
16	Horizontal velocity of the ADV-1 minus the LDA measurements of the 0.85 s period, 10 cm wave at a depth of 11 cm.	25

FIGURE		Page
17	Horizontal velocity of a 2 s wave with a height of 1.4 cm at a depth of 10.3 cm.	26
18	Plot of the absolute ADV-1 velocity variations from the LDA measurements of the 2 s period, 1.4 cm wave at a depth of 10.3 cm.	26
19	Horizontal velocity of a 2 s period wave with a height of 5 cm at a depth of 10.3 cm.	27
20	Horizontal velocity for a 2 s period wave with a height of 3.8 cm at a depth of 10.3 cm.	28
21	Horizontal velocity of the ADV-1 minus the LDA measurements for a 2 s period wave with a height of 3.8 cm at a depth of 10.3 cm.	28
22	Plot of the 10 cm significant wave horizontal velocity at a depth of 11 cm.	29
23	Horizontal velocity differences for the ADV-1 and LDA. The differences are the absolute variations of the ADV-1 values minus the LDA measurements of a 10 cm significant wave.	29
24	Horizontal velocity of a 12 cm significant wave with a maximum velocity range of $\pm 100$ cm/s selected for the ADV-1.	24
25	Horizontal velocity of a 12 cm significant wave with an ADV-1 maximum velocity range of $\pm 30$ cm/s.	31
26	Plot of the magnitude of the velocity variations of the ADV-1 from the LDA values for the 12 cm significant wave with maximum velocity range of $\pm 30$ cm/s.	31
27	Vertical velocities of the 12 cm significant wave at a depth of 11 cm with an ADV-1 maximum velocity range of $\pm 30$ cm/s.	32
28	Transverse velocity of the 12 cm significant wave at a depth of 11 cm with an ADV-1 maximum velocity range of $\pm 30$ cm/s.	33
29	Plot of the horizontal velocity the ADV-1 and LDA measure. Plot shows the ADV-1 functioning as it moves in and out of the water.	34
30	Horizontal velocity of the LDA for a 10 cm significant wave.	34



FIGURE		Page
31	Velocity profile (a) 15.2 cm in front, (b) 1.9 cm in front, (c) above, (d) 2.8 cm behind, and (e) 15.2 cm behind an 8.6 cm circular cylinder in a wave flume with a water depth of 57.2 cm.	37
32	Character of the steady, viscous flow past a cylinder in a large Reynolds number flow.	38
33	Velocity profile (a) 15.2 cm in front, (b) 1.9 cm in front, (c) above, (d) 2.8 cm behind, and (e) 15.2 cm behind a 6.1 cm circular cylinder in a wave flume with a water depth of 57.2 cm.	39
34	Velocity measurement 2.8 cm behind the 6.1 cm (2.4 in) cylinder. The ADV-1 sampling volume is along the horizontal centerline of the cylinder.	41
35	The flow around a circular cylinder.	41
36	Suggested mounting device for the ADV-1.	54

## LIST OF TABLES

TABLE		Page
1	ADV-1 and LDA comparison test parameters	14
2	Comparison of ADV-1 and LDA velocities under the crest with the theoretical values of Stokes second order.	35
3	Summary of ADV-1 and LDA comparison tests	36
4	Theoretical, $v_\phi$ and experimental, $V_x$ , horizontal velocities at a distance $r$ above the center of the 8.6 cm (3.4 in) cylinder.	42
5	Theoretical, $v_\phi$ and experimental, $V_x$ , horizontal velocities at a distance $r$ above the center of the 6.1 cm (2.4 in) cylinder.	42

# CHAPTER 1

## INTRODUCTION

### Background

Most ocean engineering laboratory research has a need to obtain current velocities. A wide variety of instruments are available to acquire this data in the laboratory facilities at Texas A&M University. These instruments include hot-wire anemometers, pitot tubes, a laser Doppler anemometer, and electromagnetic current meters. Hot-wire anemometers measure fluid velocity by sensing the changes in heat transfer from a small, electrically heated sensor exposed to the fluid motion. These anemometers require calibration for each test (Goldstein, 1983). Pitot tubes measure fluid velocity by determining the differential pressure between the high pressure of the flow at the tip of the tube and the low static pressure of the stationary fluid. Each tube only measures one velocity component. A laser Doppler anemometer (LDA) measures fluid velocities by detecting the Doppler frequency shift of laser light that is scattered by small particles moving with the fluid. Using the LDA requires the user to learn the many details of operating the system. An electromagnetic current meter (ECM) operates on the principle that a conducting fluid generates a voltage proportional to the flow rate as it passes through the magnetic field. The measured voltages are converted to velocities, and the velocities are resolved to determine each component (Goldstein, 1983). The U.S Army Engineer Waterways Experiment Station (WES) in Vicksburg, MS has developed a new current meter for laboratory use. This instrument is an acoustic flow meter capable of measuring three-dimensional flows with speeds as high as 2.5 m/s with a resolution of 0.1 mm/s, and at a sampling rate up to 25 Hz (SonTek, 1993). WES contracted the development of this instrument in conjunction with a new research initiative to study the hydrodynamics at inlets, which involves tidal flow, wave transformation, wave-induced currents, and wave-current interaction (Kraus, 1993). SonTek, Inc. in San Diego, CA, the contractor for this development, designed and manufactured this instrument, which is called the Acoustic Doppler Velocimeter (ADV-1). The ADV-1 was purchased by Texas A&M University

from SonTek, Inc. to improve the capability of making accurate and reliable measurements of fluid flow in the laboratory. Before using this instrument for research, the ADV-1 was tested in several facilities and compared to other instruments to determine it's capabilities.

### Objectives

The objective is to compare the ADV-1 with the Laser Doppler Anemometer (LDA) and a pitot tube, to measure current velocities in the flow field around a stationary cylinder, to prepare an operational manual for the ADV-1, and to suggest a mounting system for laboratory facilities.

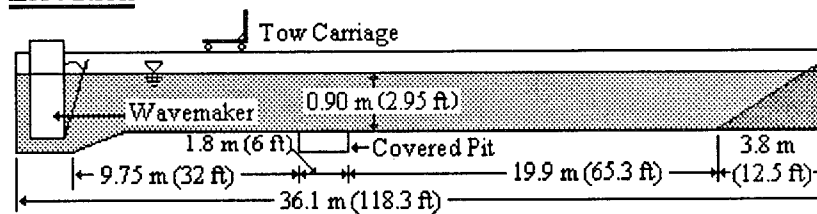
## CHAPTER 2

### EQUIPMENT AND FACILITIES

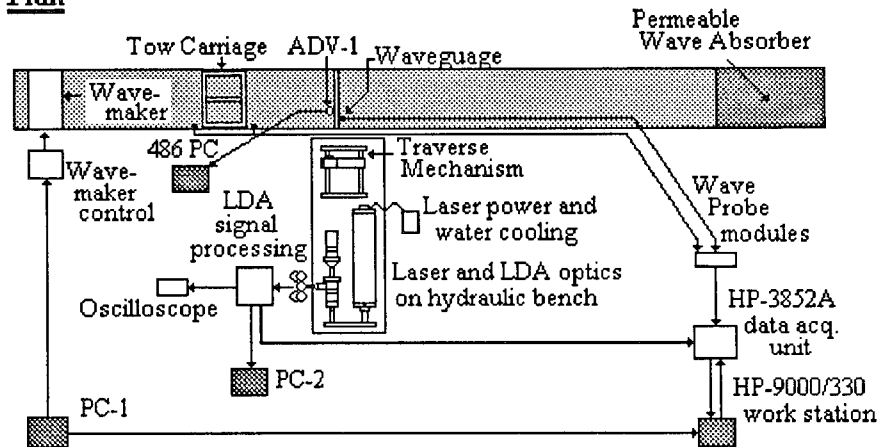
#### Wave Tank

The two-dimensional wave tank, shown in Figure 1, is located in the Texas A&M University Civil Engineering Laboratory Building. This facility was used for the ADV-1 calibration test and the LDA and ADV-1 orbital velocity comparison tests. The tank, 36.6 m (120 ft) long, 0.91 m (3 ft) wide, and 1.22 m (4 ft) deep, had a water depth of 0.90 m for all experiments. The wave channel layout and instrumentation diagram are shown in Figure 1. An absorbing beach, located 31.5 m (103.3 ft) from the wavemaker, was constructed of fibrous mats 5 cm (2 in) thick which were supported by perforated metallic sheets on a 1:3.3 slope.

#### Elevation



#### Plan



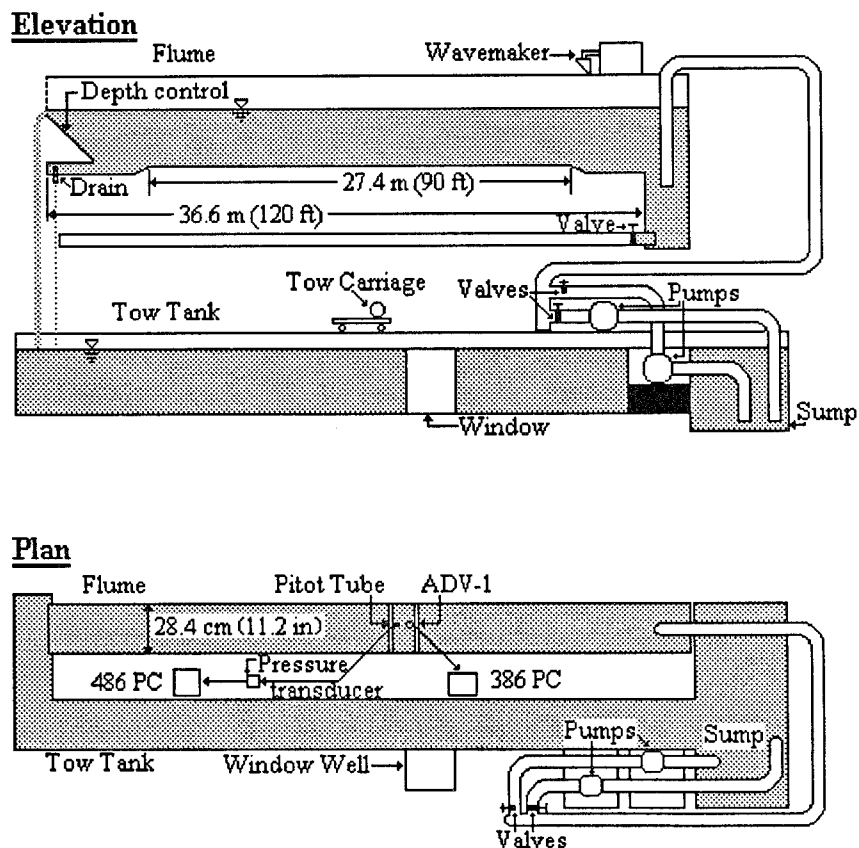
**Figure 1.** Schematic of laboratory wave tank and instrumentation.

Wave generation was provided by a computer-controlled dry-back, hinged-flap wavemaker. Power was provided by a brushless synchronous AC-servo motor containing sensors for velocity, commutation and positional information. A standard personal computer (PC-1 in Figure 1)

provided the wave generation control. The PC was interfaced to the wavemaker through an analog output card. Different software packages provided regular and random waves.

### Wave Flume

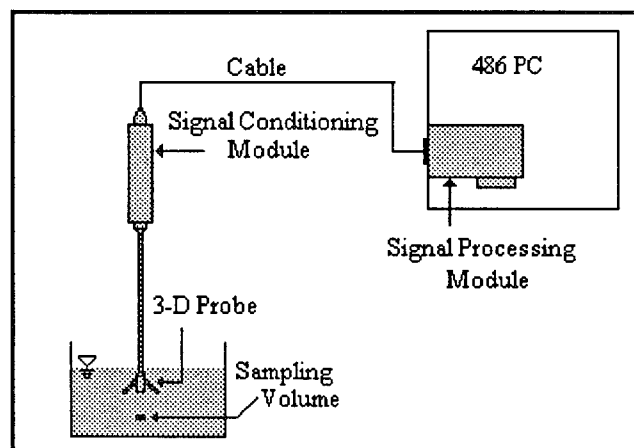
The Variable Slope Wave Flume, shown in Figure 2 and located in the Texas A&M University Hydromechanics Laboratory, was used for the ADV-1 and pitot tube horizontal velocity profile comparison tests and for measuring the velocities around a cylinder with the ADV-1. The flume is 36.5 m (120 ft) long, 0.28 m (0.93 ft) wide and 1.22 m (4.0 ft) deep. Water was supplied from a sump using a 1770 RPM pump rated at 4880 GPM. The flow rate of the water was controlled by two gate valves.



**Figure 2.** Schematic of laboratory Variable Slope Wave Flume.

### Acoustic Doppler Velocimeter (ADV-1)

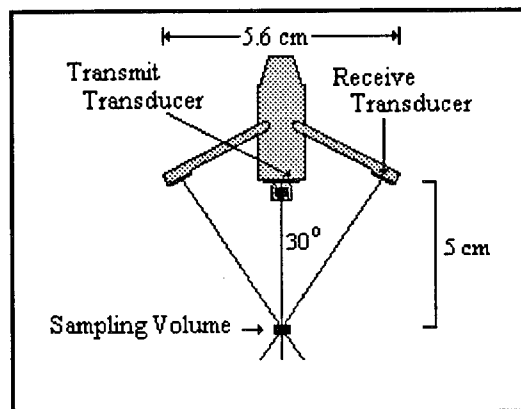
The Acoustic Doppler Velocimeter (ADV-1) system is shown in Figure 3. This system consists of four main modules: the sensor probe, signal conditioning module, signal processing module, and the controlling computer. The ADV-1 system has a horizontal velocity range of 0 to 250 cm/s with user selectable maximum horizontal velocity ranges of  $\pm 3$ , 10, 30, 100 and 250 cm/s and with a velocity resolution of 0.1 mm/s. This instrument has a controllable sampling rate from 0.1 to 25 Hz (i.e., 22.3 Hz) and a temperature operating range of 0 to 40 °C (SonTek, 1993).



**Figure 3.** The ADV-1 system.

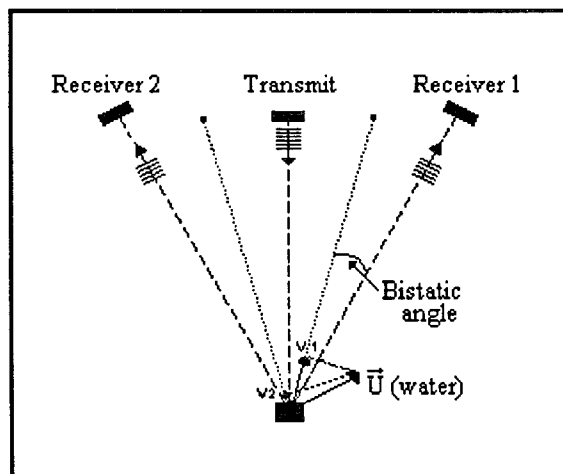
The sensor probe, shown in Figure 4, has one transmit-only transducer and three receive-only transducers. The probe is attached to a 7 mm thick, 40 cm long stem. The 10-MHz transmit transducer produces periodic short pulses along a vertical axis. The receiver transducers are mounted on short arms, 30 mm long, around the transmit transducer at 120° azimuth intervals. The beams of the receiver transducers are positioned such that they intercept the acoustic echoes of the transmit beam at a point 5 cm below the transmit transducer. Velocities are measured at the intersection of these four beams in an area defined as the sampling volume. This volume is

shaped as a cylinder, 6 mm in diameter and 3 mm long, centered at about 5 cm from the transmit transducer.



**Figure 4.** The ADV-1 probe.

The velocities are obtained using the Doppler principle. The Doppler principle states that the frequency shift between the transmit pulse and the acoustic echo is proportional to the particle velocity in the water (Urick, 1983). Figure 5 shows a simplified, two-dimensional schematic of the Doppler measurement technique in the ADV-1.



**Figure 5.** The ADV-1 measurement geometry.



As the acoustic transmit pulse travels through the water, pockets of turbulence or small particles such as micro bubbles, suspended sediments, or seeding material, scatter a small fraction of the acoustic energy. These echoes, originating at the sampling volume, are detected by the three receive transducers. The frequency of the echo is Doppler shifted due to the relative velocity of the flow with respect to the probe. The component of the flow velocity along the bisector of the transmit and receive beams is proportional to the Doppler shift measured at each receiver. Figure 5 shows a 2-D case, but this principle also permits a direct measurement of the component of the velocity vector along three different directions for the 3-D probe. For the 2-D case, the orthogonal components ( $u, w$ ) of the velocity vector can be computed by a simple coordinate transformation. Assume that the angle between the transmit beam and either receive beam in Figure 5 is  $30^\circ$  ( $\pi/6$ ). The velocities measured by receivers 1 and 2 in this case are

$$V_1 = u \cos \frac{\pi}{12} + w \sin \frac{\pi}{12} \quad (1)$$

$$V_2 = -u \cos \frac{\pi}{12} + w \cos \frac{\pi}{12} \quad (2)$$

where  $V_1$  and  $V_2$  are the velocity vectors,  $u$  and  $w$  are velocity components, and  $\pi/12$  is the half angle, or bistatic angle, between the transmit and receive beams. From Equation 1 and 2, the orthogonal components of the 2-D water velocity vector are shown in Equations 3 and 4.

$$u = \frac{V_1 - V_2}{2 \sin \frac{\pi}{12}} \quad (3)$$

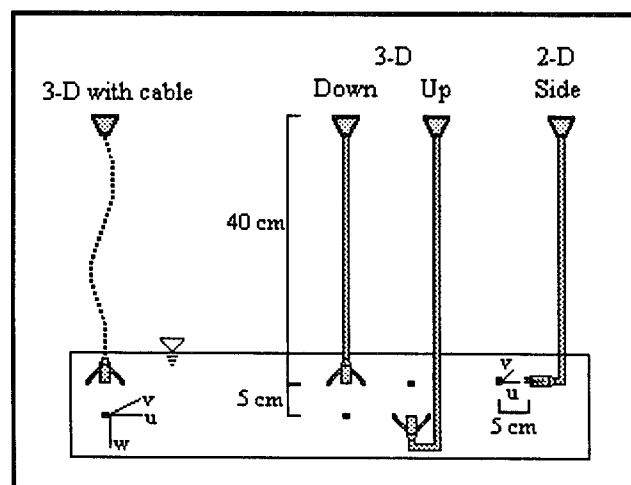
$$w = \frac{V_1 + V_2}{2 \cos \frac{\pi}{12}} \quad (4)$$

The echo must be strong enough to properly calculate the frequency shift. A weak echo will produce "noisy" velocity data. The strength of the echo is expressed in terms of the signal-to-noise ratio (SNR) with units of decibels (dB). The decibel scale is the most generally used logarithmic scale for describing sound levels. The level of a sound wave is the number of decibels by which its intensity, or energy flux density, differs from the intensity of the reference sound wave. In the case of a sound wave with intensity,  $I_1$ , and a reference intensity,  $I_2$ , the level of the sound wave is equal to:

$$N \text{ dB} = 10 \log \frac{I_1}{I_2} \quad (5)$$

The ADV software reports this value. A 20 dB SNR is needed to assure a reliable velocity measurement. Seeding material with a diameter of  $10\mu\text{m}$  is available from SonTek, Inc. for bodies of water lacking the particles to scatter the transmit pulse (SonTek, 1993).

The sensor probe and stem are easily attached and detached from the signal conditioning module. This allows for interchange of stems of various configurations. Figure 6 shows the most common probe configurations available from SonTek, Inc. The 3-D down-looking probe is the only configuration available at Texas A&M University. The sampling volume is approximately 5 cm in front of the transmit transducer for all the probes in Figure 6.



**Figure 6.** Various probe configurations.

The minimum distance from the sampling volume to a boundary is 5 mm. 3-D probes measure  $u$ ,  $v$ , and  $w$  velocity components. The side-looking 2-D probe only measures  $u$  and  $v$  velocity components. The minimum operating depth for a 3-D probe is 55 to 70 mm and for a 2-D probe is 20 to 30 mm.

The signal conditioning module, shown in Figure 3, is enclosed in a 6 cm diameter, 30 cm long anodized aluminum housing which is waterproof. This module contains circuitry required for amplifying and filtering the weak Doppler signals, for electrically coupling the acoustic transducers, and for driving the signal through the relatively long cable to the processing module. The 10 m long cable is waterproof. A 30 m long cable is also available from SonTek, Inc.

Figure 3 also shows the signal processing module. The module is a PC-compatible card which is placed in a 33-MHz 486 computer. This module performs the functions required for converting the analog Doppler signals to digital form, which are then used to estimate Doppler velocities. This module also controls the overall system timing and generates the transmit waveforms. The 486 computer controls and monitors the operation of the processing module, performs the high-level Doppler signal processing, performs coordinate system transformations and scaling, and runs the data acquisition software.

The ADV-1 data acquisition software provides a menu with controllable data collection parameters, such as sampling frequency, duration and velocity range, and an acquisition menu which displays the signal strength, data quality, and the velocity trace. The software has a program that allows the user to convert the data to an ASCII file. Appendix A discusses the operation of the software in detail.

### **Laser Doppler Anemometer (LDA)**

The laser Doppler anemometer (LDA) was used to measure horizontal and vertical orbital velocities in the two-dimensional wave tank shown in Figure 1. The LDA system was manufactured by DANTEC ELEKTRONIK. This LDA is a two-component reference beam system. It operates in a backscatter mode such that the transmitting and receiving optics are all

contained in a single modular unit. The optic setup uses a 4-watt COHERENT INNOVA-70 argon-ion laser producing a 1.5 mm cyan beam. A color beam splitter in the transmitting optics splits the cyan beam into separate blue and green beams for the measurement of the vertical and horizontal velocities, respectively. This cyan beam remained intact and passed through the optics as the reference beam. A computer-controlled electrical traverse mechanism controlled the point where the three beams intersected inside the wave tank both vertically and laterally. This intersection point is called the probe volume (Spell, 1992).

This system also operates on the Doppler principle. Laser light is reflected from the seeding particles in the probe volume. This backscattered light travels back into the receiving optics. The blue and green components are separated, and the Doppler frequency of the backscattered light is converted to a voltage. The particle velocity  $u$  is related to the Doppler frequency by

$$u = f\lambda/(2\sin\theta) \quad (6)$$

where  $\lambda$  is the wavelength of the laser light and  $\theta$  is the half angle of the beam intersection (Spell, 1992).

A personal computer (PC-2 in Figure 1) interfaced with a METRABYTE DASH-16/16f A/D board provided real-time monitoring of the velocities. The program MULTI\_SCAN (Spell, 1992) was used for the acquisition of velocity components using the HP-9000/330 workstation and the HP-3852A data acquisition unit.

### **Wave gauge**

A wave gauge was used to measure the wave elevations during the LDA and ADV-1 orbital velocity comparison tests. The twin-rod resistance-type wave gauge was manufactured by COMMERCIAL HYDRAULICS. This gauge consists of dual stainless steel rods 2-mm in diameter and 400 mm long, with a 20 mm spacing between rods. The gauge was placed 10 cm downstream of the sampling volume/probe volume as shown in Figure 1.

### Pitot Tube

A single pitot tube was used to measure velocity profiles in the Variable Slope Wave Flume as shown in Figure 2. The pitot tube measured the local pressure in the flow field. The pressure transducer then converted the pressure to a voltage reading. This voltage reading was amplified by a data acquisition card in the computer. The program ETEST (Prislin, 1993) converted this data to a velocity reading.

## CHAPTER 3

### EXPERIMENTAL PROCEDURES

#### Calibration of ADV-1

The ADV-1 was calibrated by the manufacturer before being shipped to Texas A&M. To check this calibration, the ADV-1 was attached to a tow carriage that is driven by an electrical motor and mounted on top of the wave tank shown in Figure 1. The speed of the carriage was determined by measuring the time required for a bar mounted on the carriage to trip two switches placed 243.5 cm (95.9 in) apart. The HP-9000/330 work station used the MULTI\_SCAN program to measure the time for the bar to trip each switch. The ADV-1 was continuously measuring velocities as the carriage traveled through the marked distance.

#### Comparison of ADV-1 with a Pitot Tube

The ADV-1 sampling volume was aligned with a single pitot tube in the Variable Slope Wave Flume shown in Figure 2. The ADV-1 sampling volume was positioned 1 cm in front of the pitot tube to prevent interference of the acoustic beam. The ADV-1 sampling rate was set at 25 Hz. Water depth was 40.6 cm (16 in). This water depth was selected after experimenting with the capability of the ADV-1's signal conditioning module housing being submerged. Submerging the cylindrical housing in the flow rate used for these tests caused increased vibration in the sensor probe. The larger diameter of the housing increased the drag forces on the instrument. These drag induced vibrations affected the accuracy of the velocity measurements. A water depth of 40.6 cm allowed the ADV-1 to measure the velocities in the flow field from the bottom of the flume to a point 5 cm from the free surface. To reduce pitot tube vibrations, the tube was secured in a manner to only allow a velocity profile measurement from the bottom of the flume to the middle of the water column.

Two tests were conducted to compare the ADV-1 and the pitot tube. For the first test, the instruments were placed in the center of the flume. Both instruments were lowered to the bottom

of the flume. The ADV-1 was positioned to determine the minimum distance from the sampling volume to the boundary which would allow measurement of the velocity. An accurate reading was obtained 3 mm from the bottom. As both instruments were raised in the water column, velocities were measured. The instruments were then placed 5.8 cm from the wall of the flume, and the same procedure was followed to obtain velocities in the water column. The ADV-1 again measured the velocity of the fluid with the sampling volume 3 mm from the bottom. The point of the pitot tube was 5 cm below the probe tip for all velocity measurements. Seeding of the flume was not required because the particles in the water were large enough to provide a high signal-to-noise ratio (SNR).

The pitot tube system required calibration before measuring any velocities and recalibration every hour the system was operating. For calibration, the pitot tube first obtained a zero reading without flow in the flume using the CALIBRATION (Prislin, 1992) program. The ETEST program used this zero reading to calculate the average velocity. This program obtained six measurements over a 30 s period and then averaged them for a single velocity reading. The ADV-1 measured velocities during the same 30 s time span for each selected point in the flow field. The entire data file was then averaged over the 30 s to obtain a velocity for comparison.

#### **Comparison of ADV-1 with the LDA**

In the two-dimensional, glass-walled wave tank, shown in Figure 1, the sampling volumes of the LDA and the ADV-1 were aligned by placing the laser beam at the bottom of the ADV probe and then traversing the laser beam down 5 cm below the probe. The water depth in the tank was 0.90 m (2.95 ft). The sampling volumes intersected at approximately 25 cm (9.8 in) inside the glass wall. Both the ADV-1 and LDA sampled data at 25 Hz. A wave gauge was placed downstream from the LDA and ADV-1 sampling volume. The wave gauge measured the wave elevations, using the MULTI\_SCAN program, for each test in the wave tank. The water in the wave tank was seeded with seeding material, a solution of 10  $\mu\text{m}$  hollow spheres that were large enough to provide sufficient reflection of the laser beam as well as the ADV acoustic pulse.

wave period was 2 s. The maximum velocity range was set at  $\pm 3$  cm/s for test 4, and the height of this wave was approximately 1.5 cm. In test 5, the wave height was increased to 5 cm, and the maximum velocity range was set at  $\pm 10$  cm/s. To keep the orbital velocities within the maximum velocity range of  $\pm 10$  cm/s, test 6 was conducted with a wave height of 4 cm.

Tests 7, 8, and 9 were conducted to further investigate the effect of the maximum velocity range setting and the SNR on the measured orbital velocities. The same personal computer was used to generate irregular waves from the JONSWAP wave spectrum using the YOURWAVE (Spell, 1992) program. The instrument sampling volumes were positioned 11 cm below the SWL. For test 7, a 10 cm significant wave was generated, and the selected maximum velocity range for the ADV-1 data acquisition was  $\pm 30$  cm/s. A 12 cm significant wave was generated for Test 8 with a maximum velocity range  $\pm 100$  cm/s. Another 12 cm significant wave was generated for Test 9, but the maximum velocity range was reduced to  $\pm 30$  cm/s. The ADV-1 probe came out of the water several times during tests 8 and 9. The ADV-1 recovered quickly and began collecting data as designed.

The LDA data acquisition was accomplished with the MULTI\_SCAN program on the HP-9000/330 work station. Orbital velocity measurements in each test were completed before the wave reflections entered the test area. The LDA and ADV-1 did not collect data at precisely the same time. This time difference was compensated by adjusting the beginning of the velocity data files to match as closely as possible.

### **Flow Field Around a Cylinder**

The ADV-1 was used to measure the velocities around two different cylinders in the Variable Slope Wave Flume shown in Figure 2. One test used an 8.62 cm (3.39 in) outside diameter cylinder placed horizontally in the flume, and the second test used a 6.08 cm (2.39 in) outside diameter cylinder also placed horizontally in the flume. The water depth in the flume for each test was 57.15 cm (22.5 in). The center of the cylinders were positioned 25.75 cm (10.14 in) below



Table 1 shows the test parameters of each ADV-1 and LDA test. For test 1, the ADV-1 and LDA sampling volumes were positioned 11 cm below the still water level (SWL). A regular wave was generated using the REGWAVE1 (Spell, 1992) program. The wave had a period of 0.85 s and a height of 6.2 cm. A maximum velocity range of  $\pm 10$  cm/s was selected on the setup screen of the ADV-1 software. A regular wave with the same period and a height of 8.5 cm was similarly generated for test 2. The sampling volumes remained in the same location, but the maximum velocity range was increased to  $\pm 30$  cm/s. Test 3 also had a regular wave, but it had a period of 0.85 s and a height of 10 cm. The ADV-1 and LDA sampling volumes remained 11 cm below the SWL, and the maximum velocity range remained at  $\pm 30$  cm/s.

Test No.	Wave period (s)	Wave Height (cm)	Max Vel. Range(cm/s)
1	0.85	6.2	$\pm 10$
2	0.85	8.5	$\pm 30$
3	0.85	10	$\pm 30$
4	2	1.4	$\pm 3$
5	2	5	$\pm 10$
6	2	4	$\pm 10$
7	2	10 cm sig. wave	$\pm 30$
8	2	12 cm sig. wave	$\pm 100$
9	2	12 cm sig. wave	$\pm 30$

**Table 1.** ADV-1 and LDA comparison test parameters.

The sampling volumes of the ADV-1 and LDA were positioned 10.3 cm below the SWL for tests 4, 5, and 6. Regular waves were again generated using the REGWAVE1 program, and each

still water level (SWL). All data were collected at a sampling rate of 25 Hz. A maximum velocity range of  $\pm 100$  cm/s was selected for the ADV-1 data acquisition software.

Velocity profiles were obtained at five positions in the flow field around the 8.62 cm (3.4 in) cylinder. These positions were 15.2 cm (6 in) in front of the cylinder, 1.9 cm (0.75 in) in front of the cylinder, above the cylinder, 2.8 cm (1.1 in) behind the cylinder and 15.2 cm (6 in) behind the cylinder. The same positions were also chosen to measure the velocity profiles in the flow field around the 6.08 cm (2.4 in) cylinder. The water in the wave flume did not require seeding because the fluid particles provided sufficient scattering of the transmit beam for a sufficiently high SNR.

## CHAPTER 4

### RESULTS

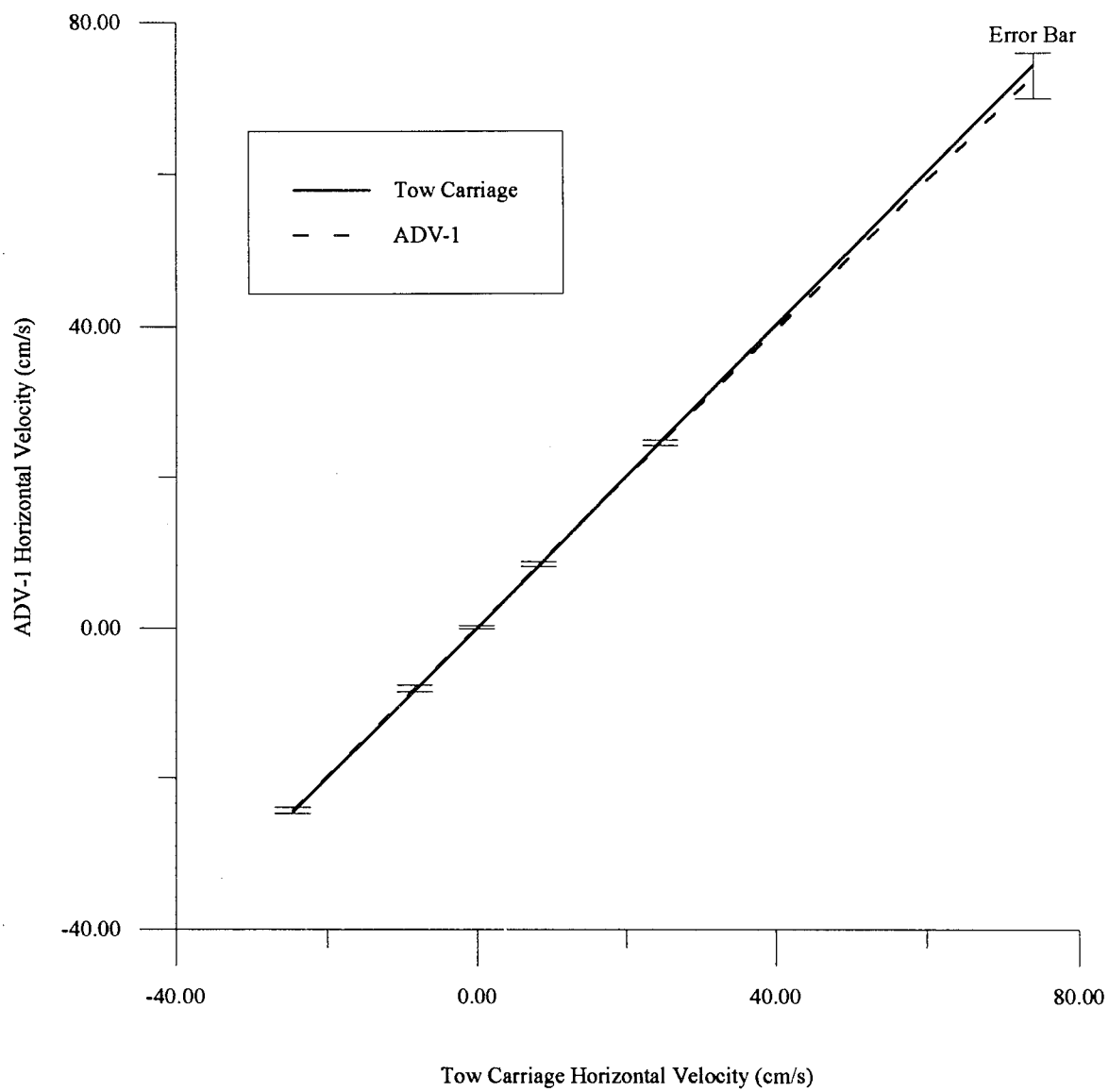
#### Calibration of ADV-1

The ADV-1 measures horizontal velocities for two different ranges ( $\pm 30$ ,  $100$  cm/s). The  $\pm 100$  cm/s maximum velocity range was selected to measure the maximum velocity of the tow carriage, the  $\pm 30$  cm/s range was used for the lower tow carriage speeds. Figure 7 compares the tow carriage horizontal velocities and the ADV-1 horizontal velocities. The error bars in Figure 7 represent the difference between the calculated tow carriage velocity and the ADV-1 measured horizontal velocity. The five velocities the ADV-1 measured in the  $\pm 30$  cm/s range have a 1.5 % difference from the carriage velocities. All six velocity measurements have a 1.6 % difference from the carriage velocities.

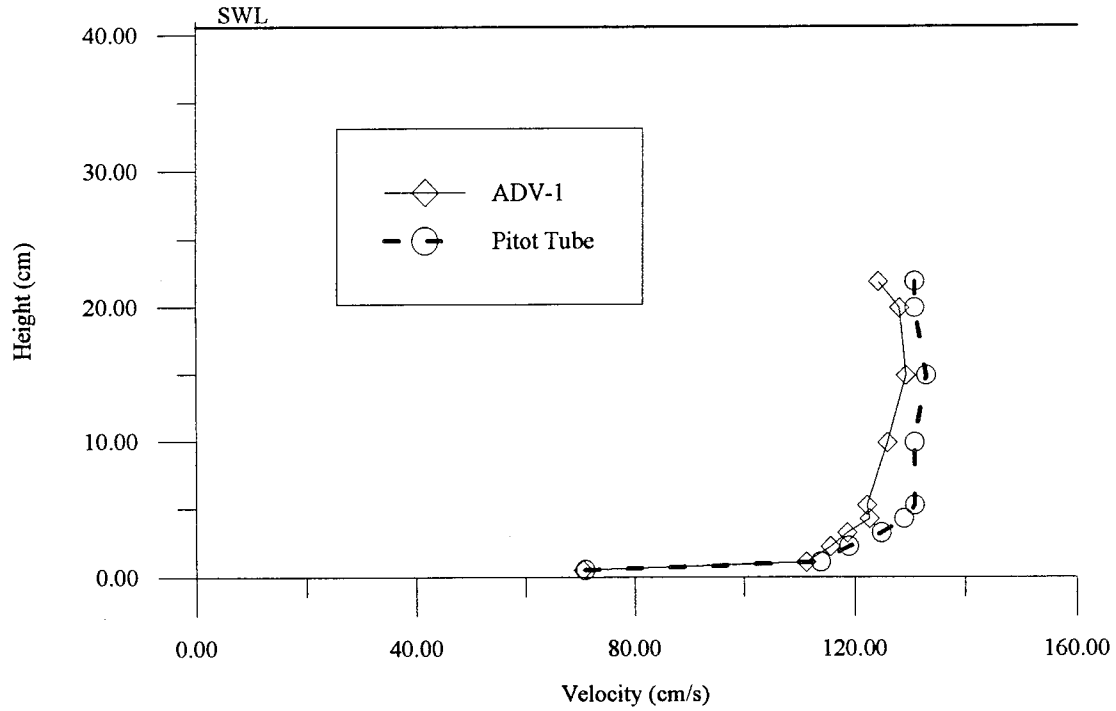
From design specifications, the statistical uncertainty of the ADV-1 is 1 to 15 mm/s for each sample at 25 Hz (SonTek, 1993). The statistical uncertainty of the measurements within the  $\pm 30$  cm/s velocity range is 1.70 mm/s, and the uncertainty for all six measurements is 3.92 mm/s.

#### Comparison of the ADV-1 and a Pitot Tube

The pitot tube is commonly used to measure velocity profiles in the laboratory wave tank and flume. The ADV-1 is also capable of measuring these velocity profiles. Figure 8 shows the velocity profiles obtained with the ADV-1 and pitot tube in the center of the wave flume. The ADV-1 measures a velocity with the sampling volume 2 to 3 mm from the bottom of the flume. This sampling volume is closer to the boundary than the minimum distance suggested in the ADV-1 design specifications. The SNR for the ADV-1 was 54 dB. The ADV-1 and Pitot Tube velocities have a 3.5 % difference, and the pitot tube velocities are consistently equal to or larger than the ADV-1 velocities.



**Figure 7.** Calibration of the ADV-1 using a tow carriage on a wave tank



**Figure 8.** ADV-1 and pitot tube horizontal velocity profiles in the center of the flume.

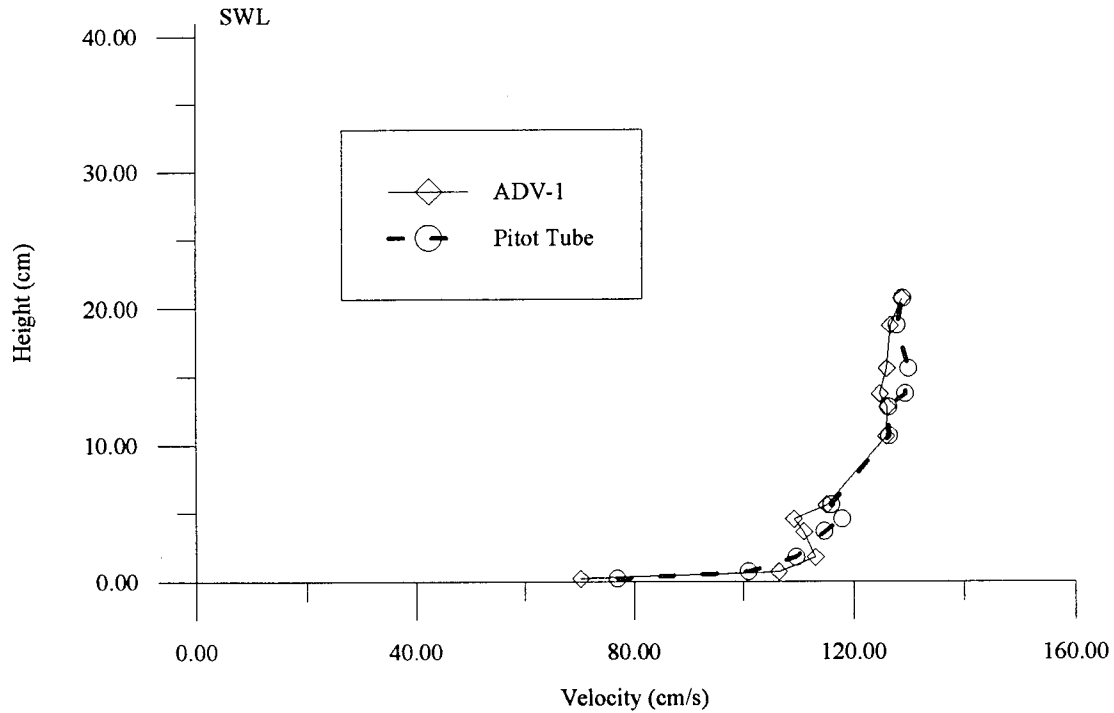
Figure 9 compares the velocity profiles the ADV-1 and the Pitot Tube measured at a distance of 5.8 cm from the wall. The ADV-1 again measures a velocity closer to the boundary than suggested. The sampling volume is 2 to 3 mm from the bottom for this measurement. The ADV-1 again had a high SNR of 58 dB. There is a 3.2 % difference between the velocities of the ADV-1 and the pitot tube.

Vanoni demonstrated that the Prandtl universal logarithmic velocity-distribution law for pipes also applies to a two-dimensional open channel. This equation for pipes is

$$u = u_o - 2.5\sqrt{\tau_o/\rho} \ln \frac{r_o}{r_o - r} \quad (7)$$

where  $u_o$  is the free-stream velocity of the flow,  $u$  is the velocity at a distance  $r$  from the wall,  $r_o$  is the radius of the pipe,  $\rho$  is the density, and  $\tau_o$  is the shear stress at the wall surface. For the open channel case, the equation is

$$\frac{u - u_o}{\sqrt{g y_o S}} = \frac{2.3}{K} \log \frac{y}{y_o} \quad (8)$$



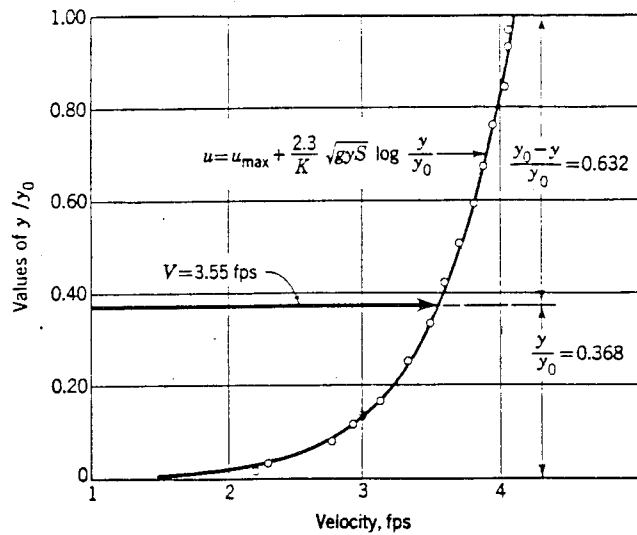
**Figure 9.** ADV-1 and pitot tube horizontal velocity profiles near the wall of the flume.

where  $y_o$  is the depth of water in channel,  $u$  is the velocity at a distance  $y$  from channel bottom,  $u_o$  is the maximum velocity,  $K$  is the von Kármán constant ( $K = 0.40$  for clear water),  $S$  is the slope of the channel, and  $g$  is the gravitational acceleration. The expression is integrated over the depth to produce the relationship

$$u = V + \frac{1}{K} \sqrt{g y_o S} \left( 1 + 2.3 \log \frac{y}{y_o} \right) \quad (9)$$

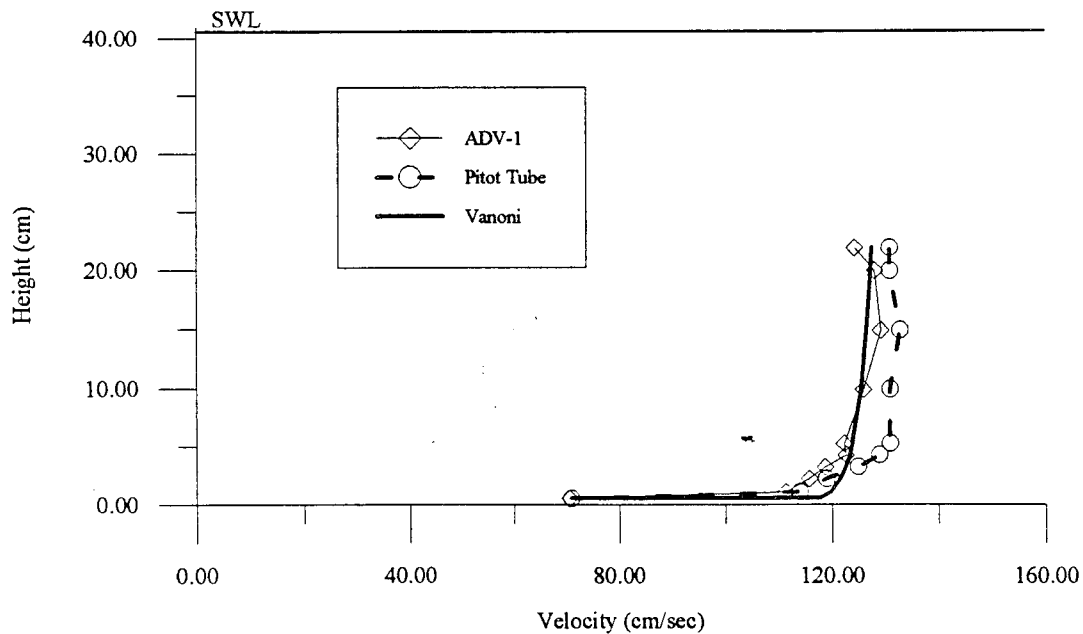
which expresses the distribution law in terms of the mean velocity  $V$ . This equation is plotted in Figure 10, along with velocity measurements obtained at the center of a rectangular flume 0.84 m (2.77 ft) wide with a water depth of 0.18 m (0.59 ft) (Daugherty, Franzini, and Finnemore, 1985).

Figure 11 is a plot of the Vanoni method with the experimental data. The Vanoni method uses Equation 6 to develop the curve. The maximum velocity the ADV-1 measured is the  $u_o$ , or  $u_{\max}$ , value.



**Figure 10.** Velocity profile at center of flume 0.84 m (2.77 ft) wide for a flow 0.18 m (0.59 ft) deep. (Daugherty, Franzini, and Finnemore, 1985 from Vanoni, 1941)

The maximum velocity the ADV-1 measured is the  $u_o$ , or  $u_{max}$ , value. The ADV-1 experimental data and the Vanoni method values have a 2.5 % difference. The pitot tube velocities and the Vanoni method values have a 3.8 % difference.



**Figure 11.** A plot of the Vanoni method versus experimental velocity profiles in the center of the flume.

### ADV-1 and LDA Comparison

The ADV-1 is capable of measuring all three velocity components of wave induced water particle velocities while the LDA is only capable of measuring the horizontal and vertical components. Tests 1, 2, and 3 focus on comparing the horizontal velocity component measured by each instrument at a depth of 11 cm below the SWL. Figure 12 shows the horizontal velocities of test 1 which has a 6.2 cm wave height with a period of 0.85 s. The maximum velocity range of the ADV-1 is set at  $\pm 10$  cm/s, but most of the horizontal crest and trough velocities measured by the ADV-1 are outside the velocity range. Since the velocity data is outside the velocity range, and the SNR of 18 dB is lower than suggested level of 20 dB, the collected data is noisy and invalid for analysis with the LDA data. Figure 13 is a plot of the wave elevations of the 6.2 cm wave height with a period of 0.85 s. As expected, the wave amplitude is largest in the crest.

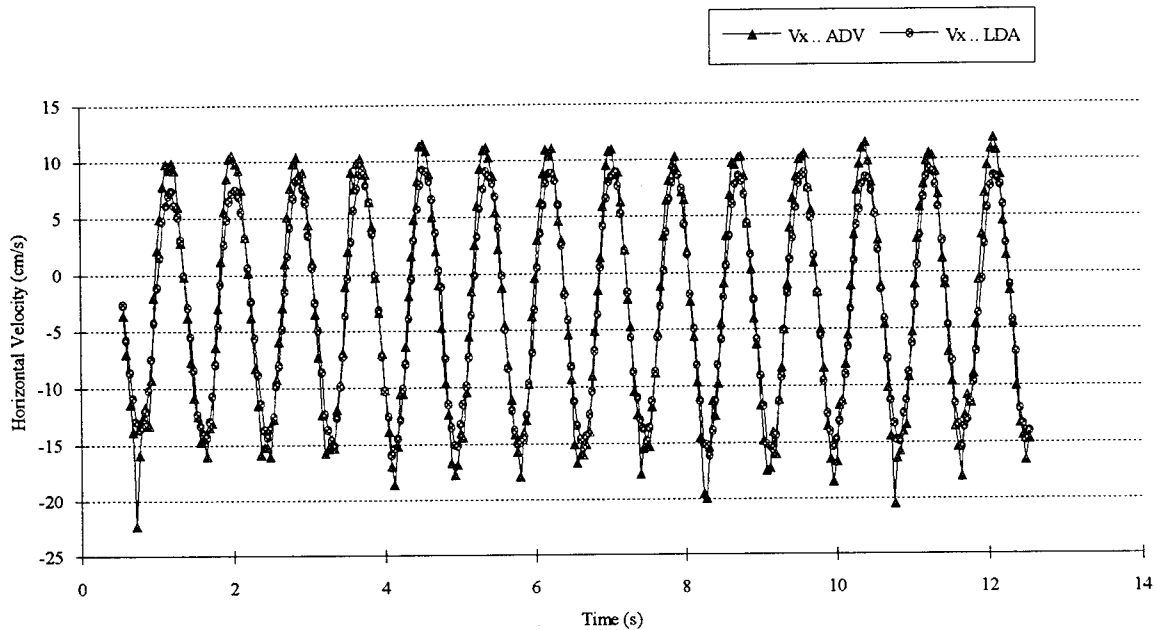
Figure 14 shows the horizontal velocities measured by the ADV-1 and LDA in test 2. This is a plot of a 0.85 s period wave with a height of 8.5 cm. Since this wave height is larger than the wave in test 1, the maximum velocity range is increased to  $\pm 30$  cm/s to ensure all measured velocities are within the maximum range. The SNR of 18 dB is lower than suggested. The horizontal velocities are within the velocity range, but the data is noisy because the SNR is low.

For test 3, the horizontal velocities of a wave with a height of 10 cm and a period of 0.85 s are shown in Figure 15. The SNR was 20 dB, which is stronger than tests 1 and 2. The higher SNR means the measured velocities have less variability. The maximum velocity range remains at  $\pm 30$  cm/s. Most of the orbital velocities the ADV-1 measures are within the velocity range. The horizontal velocities in Figure 15 are adequate for comparison with the LDA because the SNR is at the suggested level and the measured velocities are within the velocity range.

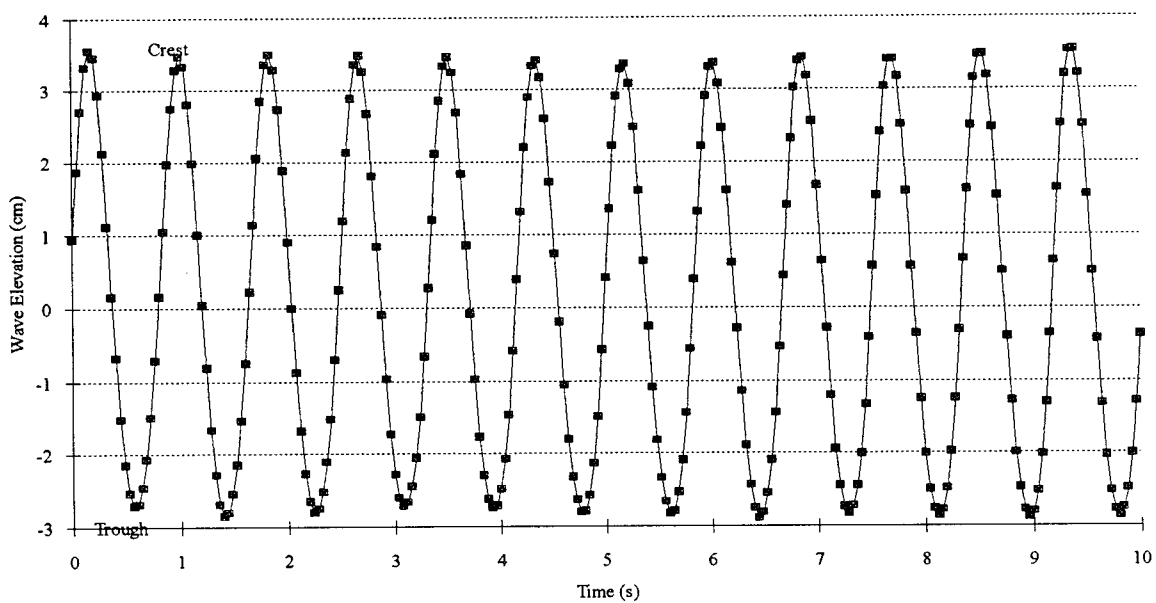
The horizontal velocities over one wavelength, from 2.35 to 3.2 s, are averaged. There is an 8.0 % difference between the ADV-1 and LDA measurements. Figure 16 is a plot of the ADV-1 measured horizontal velocities minus velocities the LDA measured over one wavelength occurring between 2.35 and 3.2 s. The velocity differences relate to the magnitudes of the



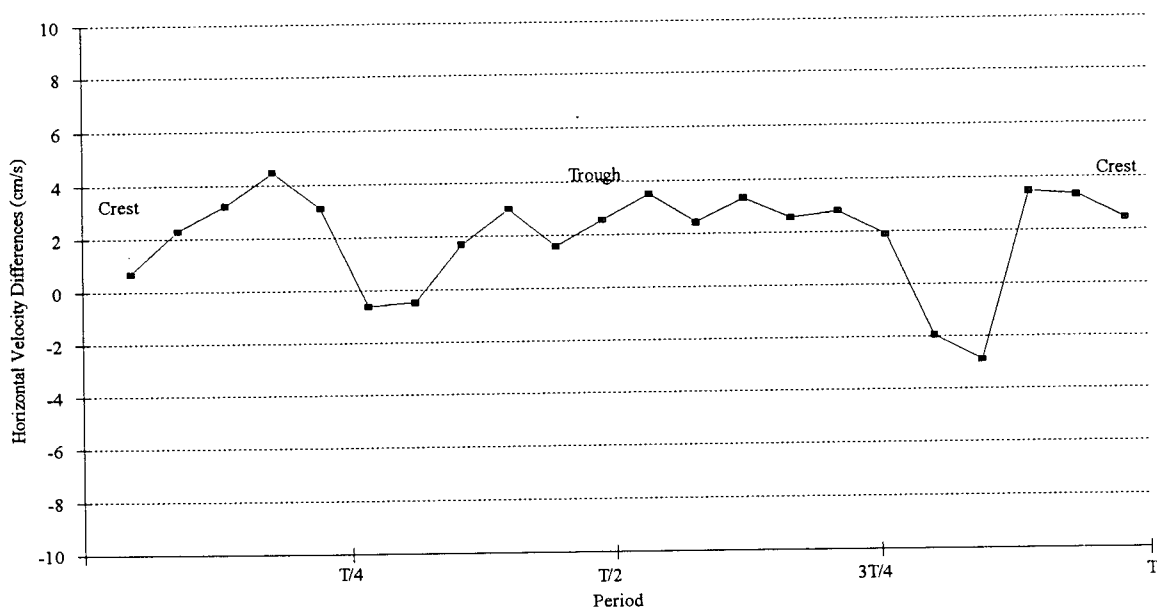
measurements. The ADV-1 measured velocities are 1.84 cm/s on the average higher than those obtained with the LDA.



**Figure 12.** Horizontal velocity of a wave with a height of 6.2 cm, 11 cm below SWL from test 1.



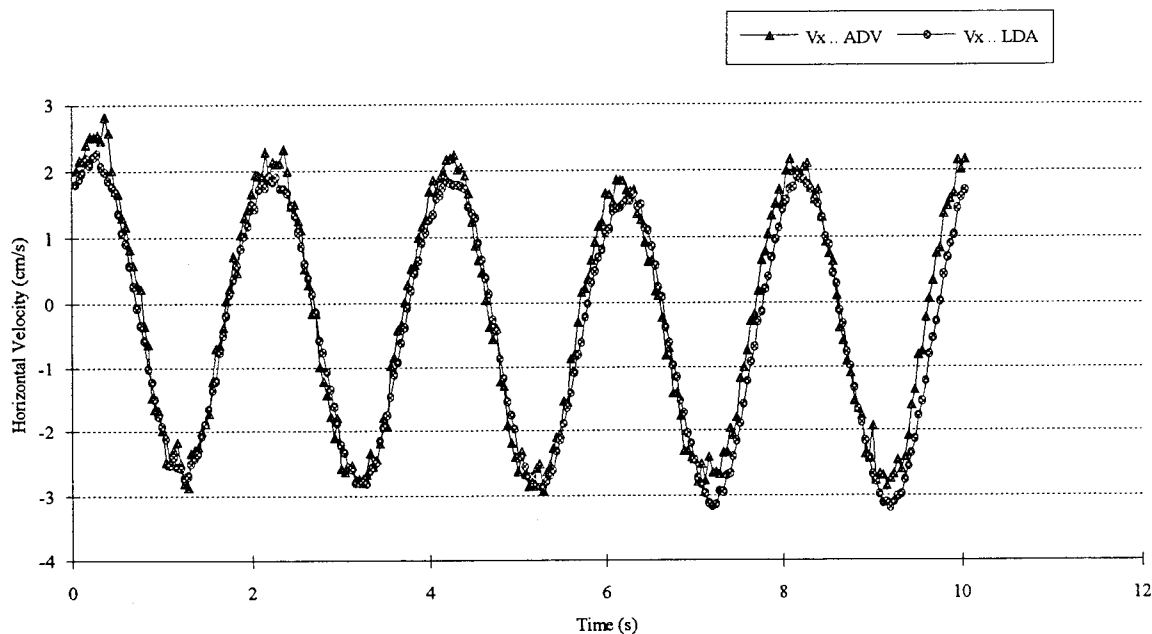
**Figure 13.** Wave elevation for the 6.2 cm wave height, 0.85 s period wave.



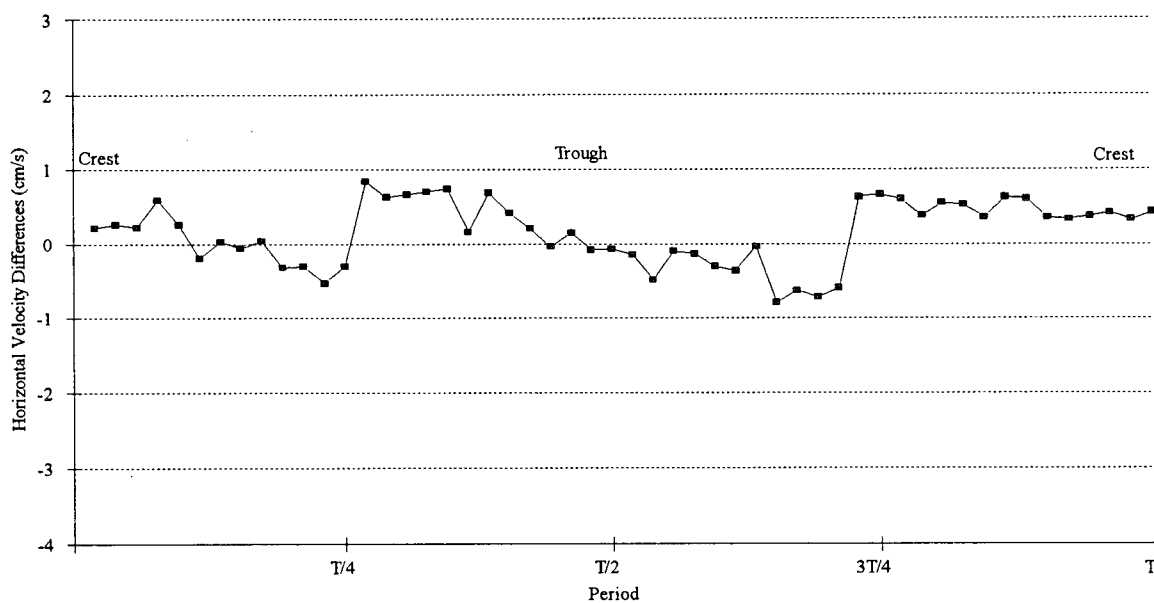
**Figure 16.** Horizontal velocity of the ADV-1 minus the LDA measurements of the 0.85 s period, 10 cm wave at a depth of 11 cm.

Tests 4, 5, and 6 further investigate the capabilities of the ADV-1. With the sampling volumes 10.3 cm below the SWL, test 4 has a regular wave with a 2 s period and height of 1.4 cm. Figure 17 shows the horizontal velocity of this wave. A SNR of 20 dB is measured, and all ADV-1 measured velocities are within the maximum velocity range of  $\pm 3$  cm/s. Since the SNR is at the suggested level, an analysis of these velocities are shown in Figure 18. This is a plot of the horizontal velocity differences over one wavelength, from 2.24 to 4.24 s in Figure 17. The magnitude of the ADV-1 velocities differ from the LDA velocities by an average 0.15 cm/s.

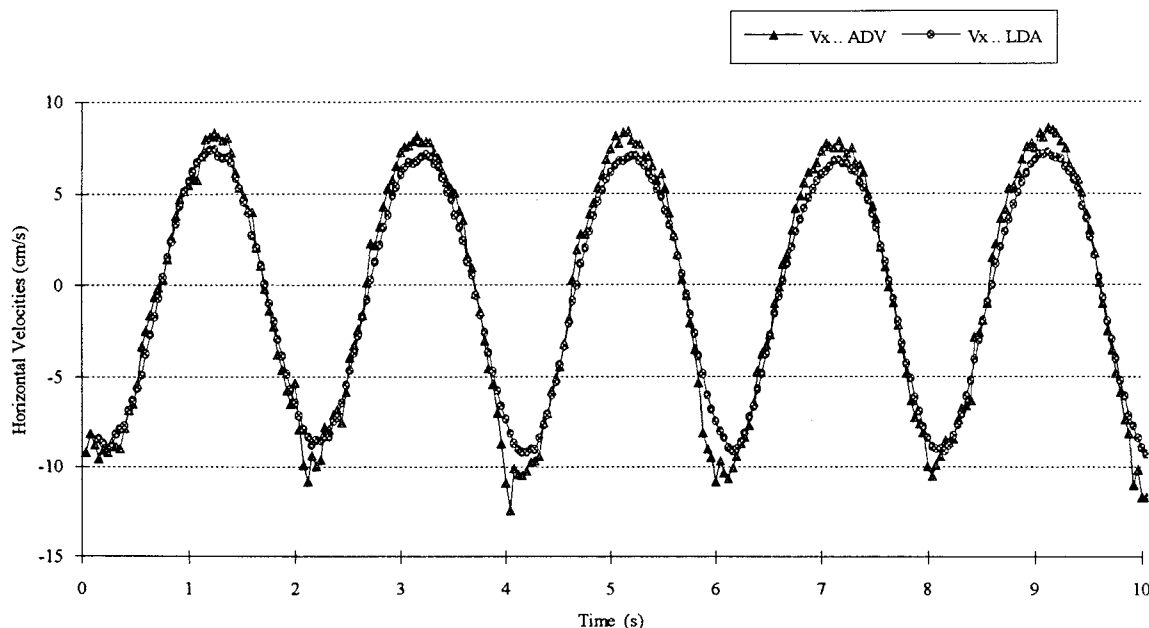
Figure 19 shows a 2 s wave with a height of 5 cm from test 5. The data are recorded with a SNR of 20 dB, and the maximum velocity range is set  $\pm 10$  cm/s because the wave height is higher than test 4. Since the measured horizontal velocities in the trough are outside the ADV-1 velocity range, the data points are inaccurate. Exceeding the maximum velocity range produces the spikes seen in the trough velocities of Figure 19.



**Figure 17.** Horizontal velocity of a 2 s wave with a height of 1.4 cm at a depth of 10.3 cm.



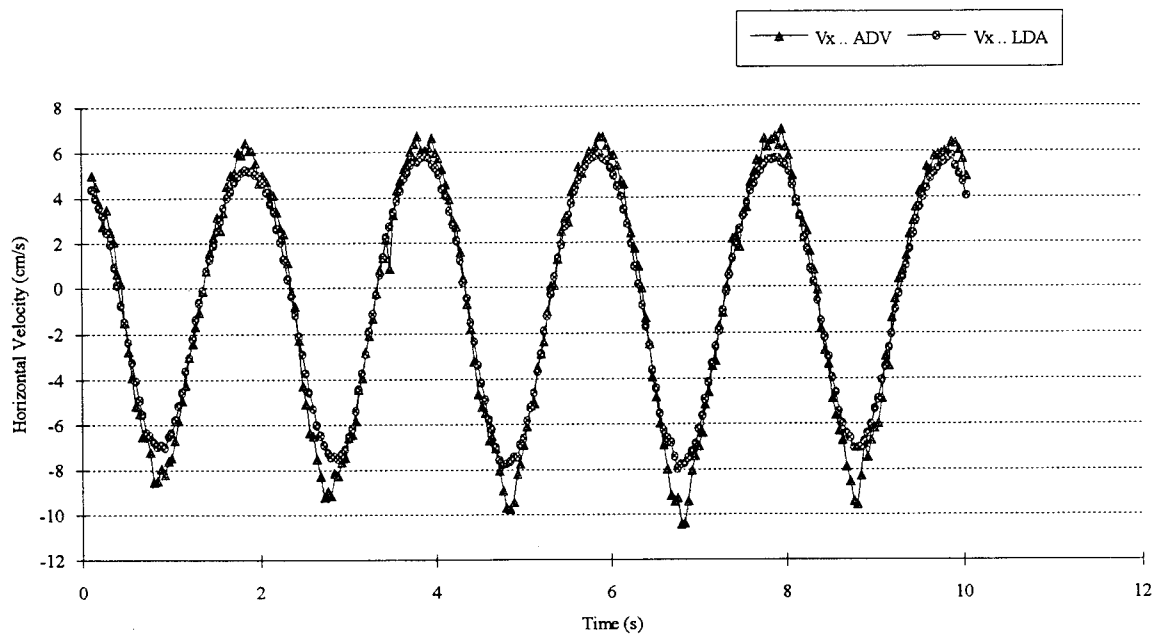
**Figure 18.** Plot of the absolute ADV-1 velocity variations from the LDA measurements of the 2 s period, 1.4 cm wave at a depth of 10.3 cm.



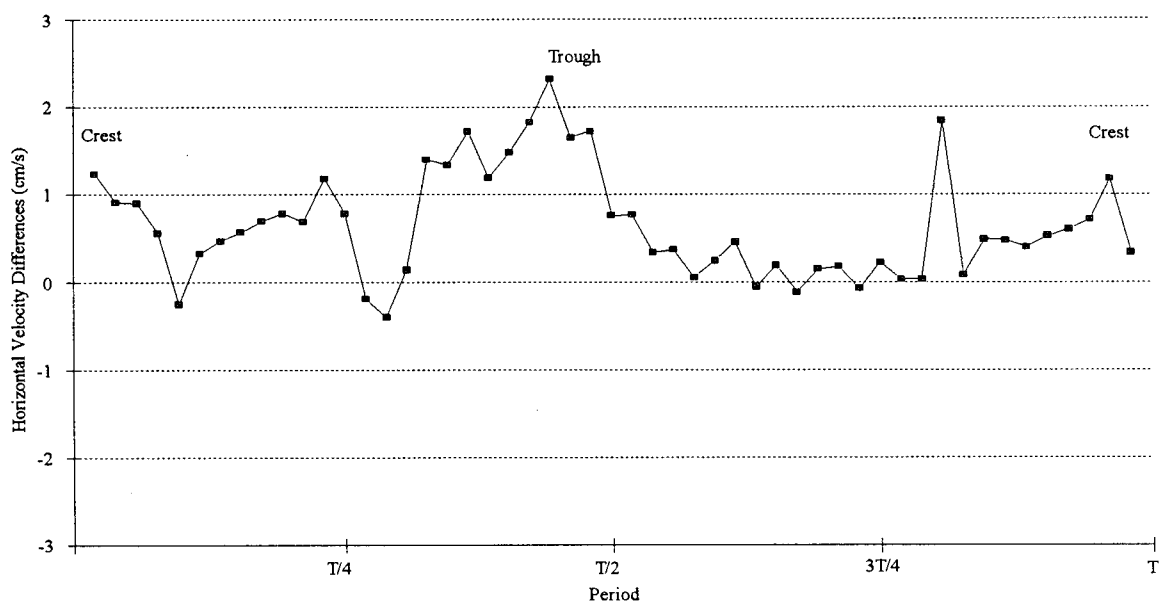
**Figure 19.** Horizontal velocity of a 2 s period wave with a height of 5 cm at a depth of 10.3 cm.

The plot in Figure 20 is the regular wave, from test 6, with a height of 3.8 cm and a 2 s period. The SNR is 20 dB, and the maximum velocity range is set at  $\pm 10$  cm/s. With the wave height of test 5 reduced for this test, the majority of the horizontal velocities are within the velocity range. The data is compared in Figure 21. This figure shows the horizontal velocity differences of the ADV-1 and the LDA from Figure 20. These differences are along one wavelength, occurring between 1.8 and 3.8 s. The average magnitude of the ADV-1 velocities is 0.66 cm/s higher than the LDA velocities.

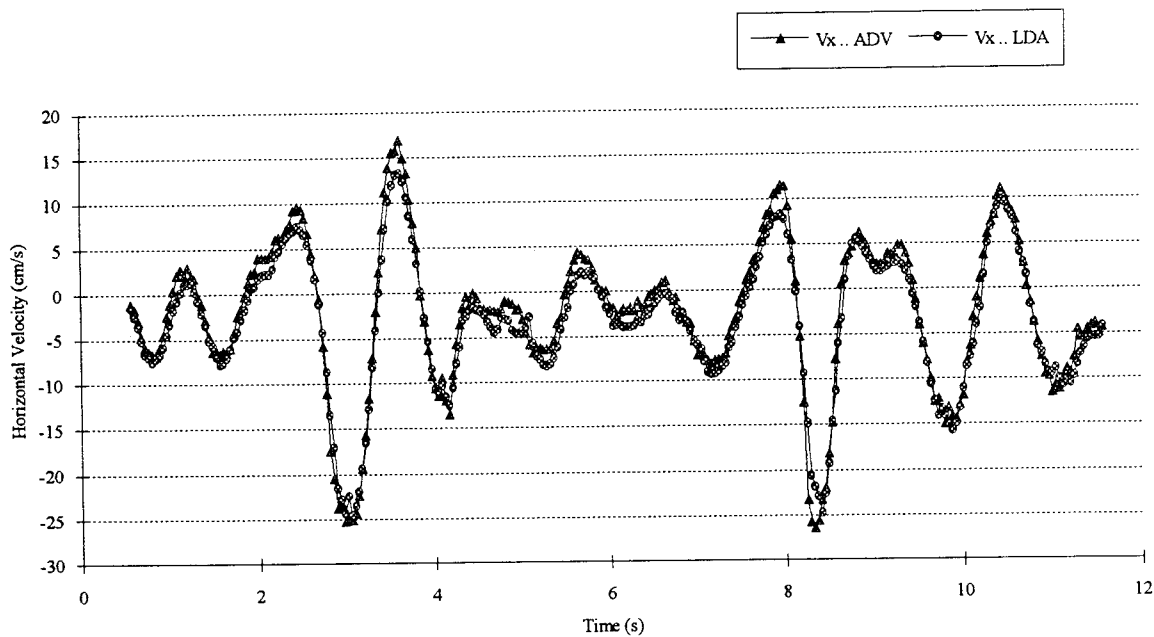
Significant waves are generated for tests 7, 8, and 9 to further investigate the effect of the maximum velocity range setting and the SNR on the measured orbital velocities. The instrument sampling volumes are 11 cm below the SWL. A 10 cm significant wave is generated for test 7, and the maximum velocity range is set at  $\pm 30$  cm/s. The SNR was 20 dB. Figure 22 is a plot of the horizontal velocities in test 7. These velocity magnitudes are compared in Figure 23. The measured ADV-1 and LDA velocities have an average difference of 0.85 cm/s between 1 and 4 s.



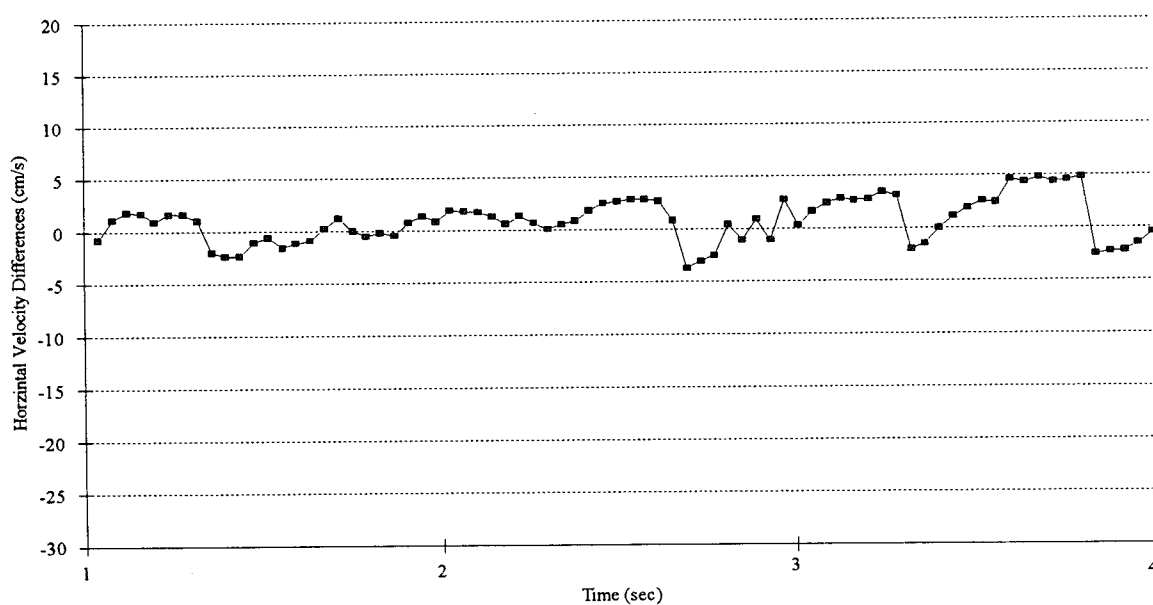
**Figure 20.** Horizontal velocity for a 2 s period wave with a height of 3.8 cm at a depth of 10.3 cm.



**Figure 21.** Horizontal velocity of the ADV-1 minus the LDA measurements for a 2 s period wave with a height of 3.8 cm at a depth of 10.3 cm.



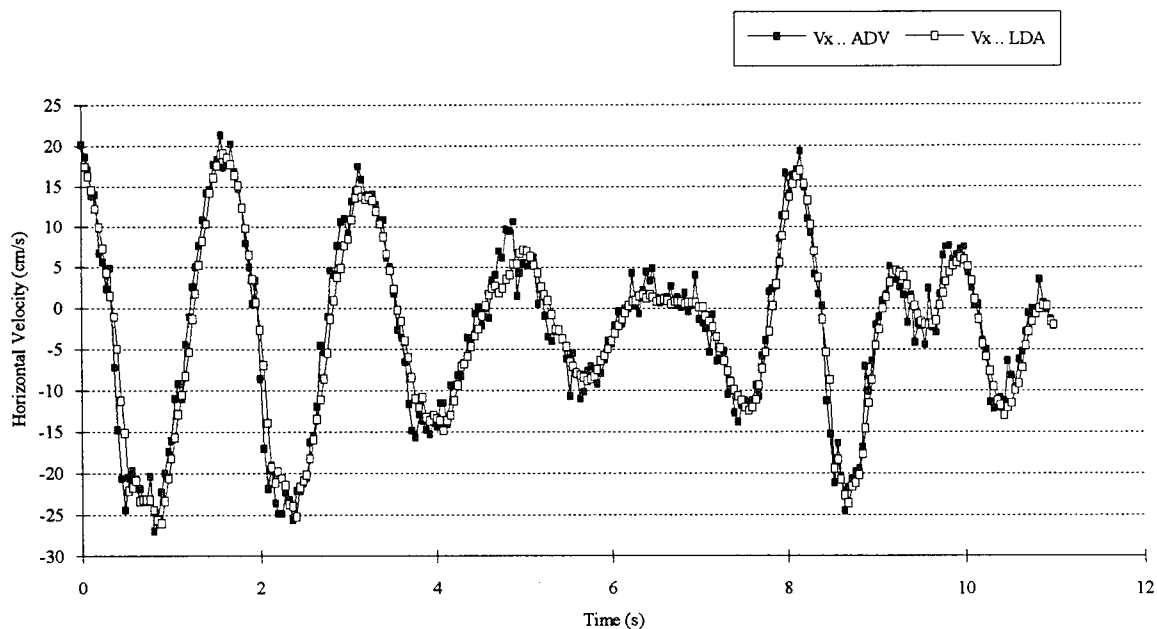
**Figure 22.** Plot of a JONSWAP wave spectrum 10 cm significant wave horizontal velocity at a depth of 11 cm with a peak period of 2 s.



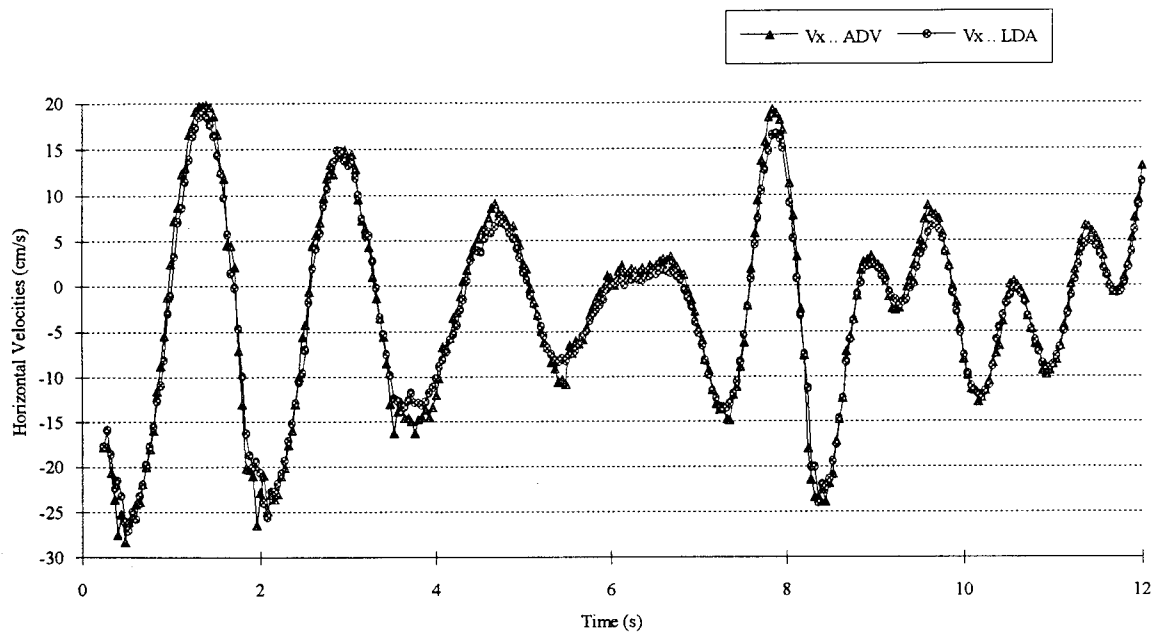
**Figure 23.** Horizontal velocity differences for the ADV-1 and LDA. The differences are the absolute variations of the ADV-1 values from the LDA measurements of the 10 cm significant wave.

For test 8, a 12 cm significant wave is generated and the maximum velocity range of the ADV-1 is  $\pm 100$  cm/s. The horizontal velocities in Figure 24 were measured with a SNR of 22 dB. There are numerous spikes along the ADV-1 horizontal velocity trace. Since the SNR is high, the spikes are probably a result of the maximum velocity range setting being too high. The velocity range should be set at the lowest possible level when collecting data.

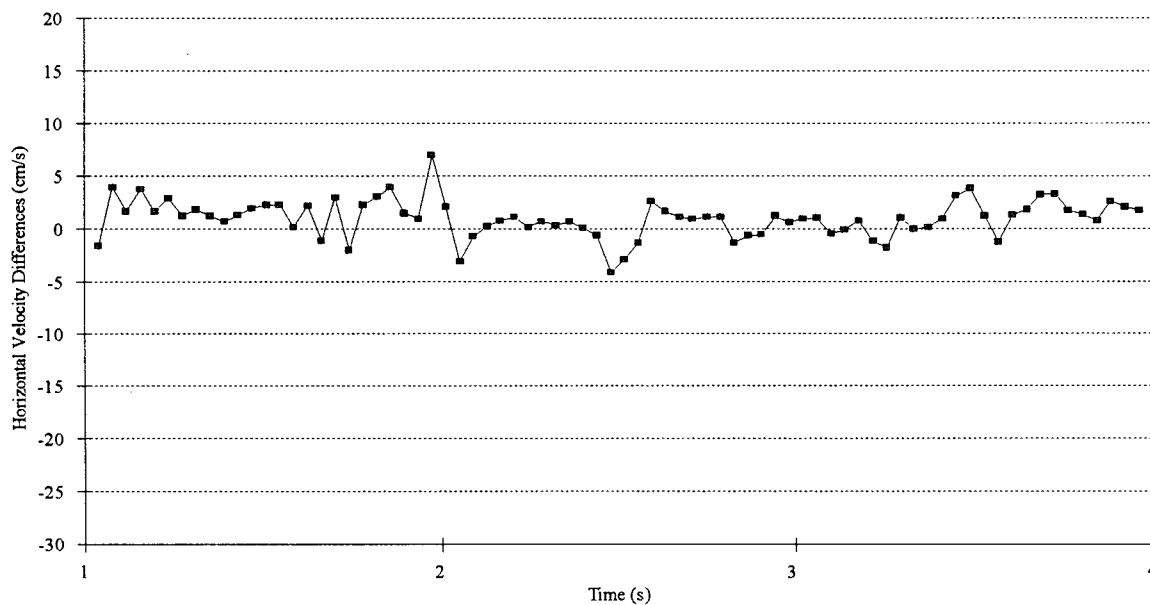
The 12 cm significant wave is generated again for test 9, and the velocity range is now set at  $\pm 30$  cm/s. Figure 25 shows the horizontal velocities from this test. A SNR of 22 dB is strong enough to ensure the collected data are good. By reducing the maximum velocity range from  $\pm 100$  cm/s, the spikes along the ADV-1 trace are removed. Since the SNR is strong and the ADV-1 velocity variations are minimal, a comparison of the measured ADV-1 and LDA velocities is shown in Figure 26. The average magnitude of the ADV-1 and LDA velocity differences is 1.0 cm/s.



**Figure 24.** Horizontal velocity of a 12 cm significant wave with a maximum velocity range of 100 cm/s selected for the ADV-1.



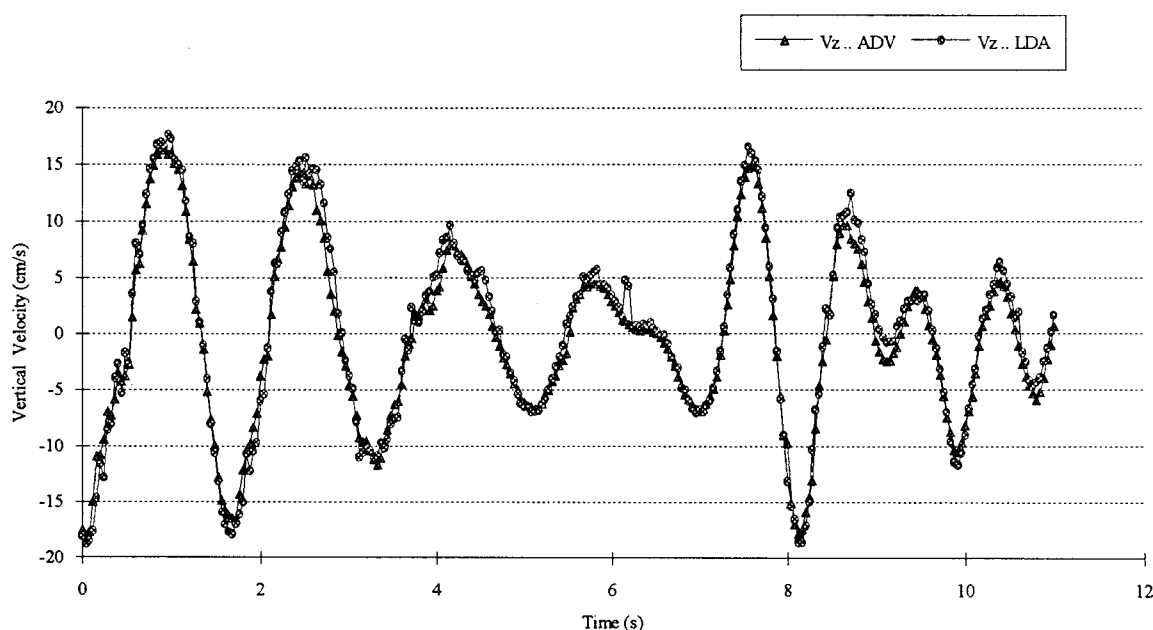
**Figure 25.** Horizontal velocity of a 12 cm significant wave with an ADV-1 maximum velocity range of  $\pm 30$  cm/s.



**Figure 26.** Plot of the magnitude of the velocity variations of the ADV-1 from the LDA values for the 12 cm significant wave and maximum velocity range of  $\pm 30$  cm/s.

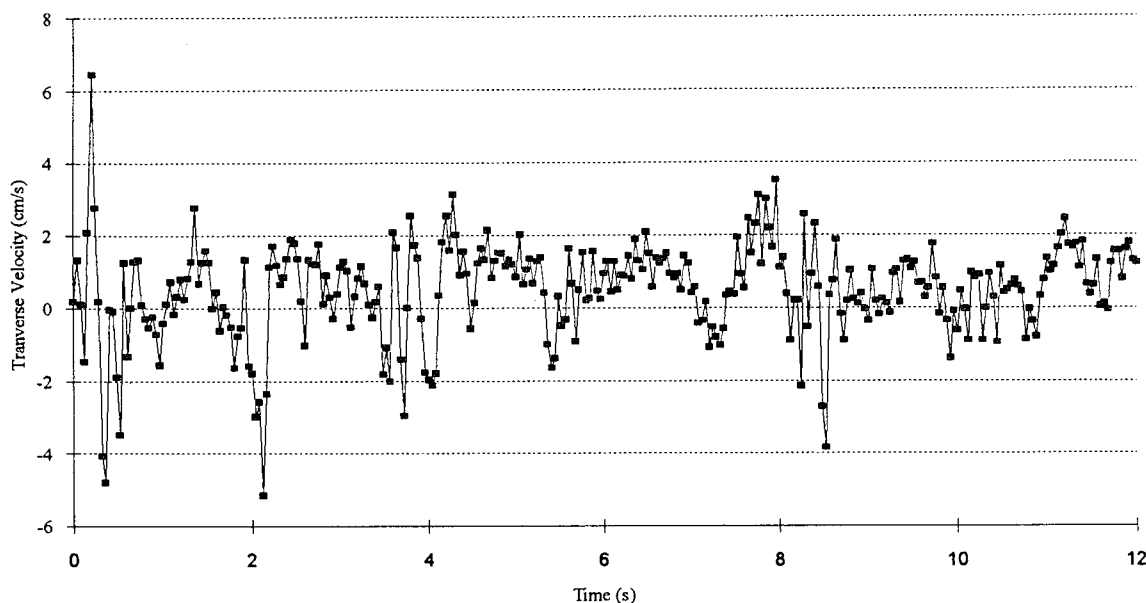


To this point, only horizontal velocities are compared. Figure 27 shows the comparison of the ADV-1 and LDA vertical velocities for the 12 cm significant wave with a maximum velocity range of  $\pm 30$  cm/s. The ADV-1 average vertical velocity is 0.93 cm/s lower than the LDA, between 1 and 4 s. The ADV-1 also measures the wave velocity of the 12 cm significant wave across the tank, and Figure 28 shows these transverse velocities. The LDA is not capable of measuring these velocities. The transverse velocities should be near zero if the instrument is aligned correctly, and a transverse wave is not present. This feature can be used to align the x-axis of the ADV-1 probe.



**Figure 27.** Vertical velocities of the 12 cm significant wave at a depth of 11 cm with an ADV-1 maximum velocity range of  $\pm 30$  cm/s

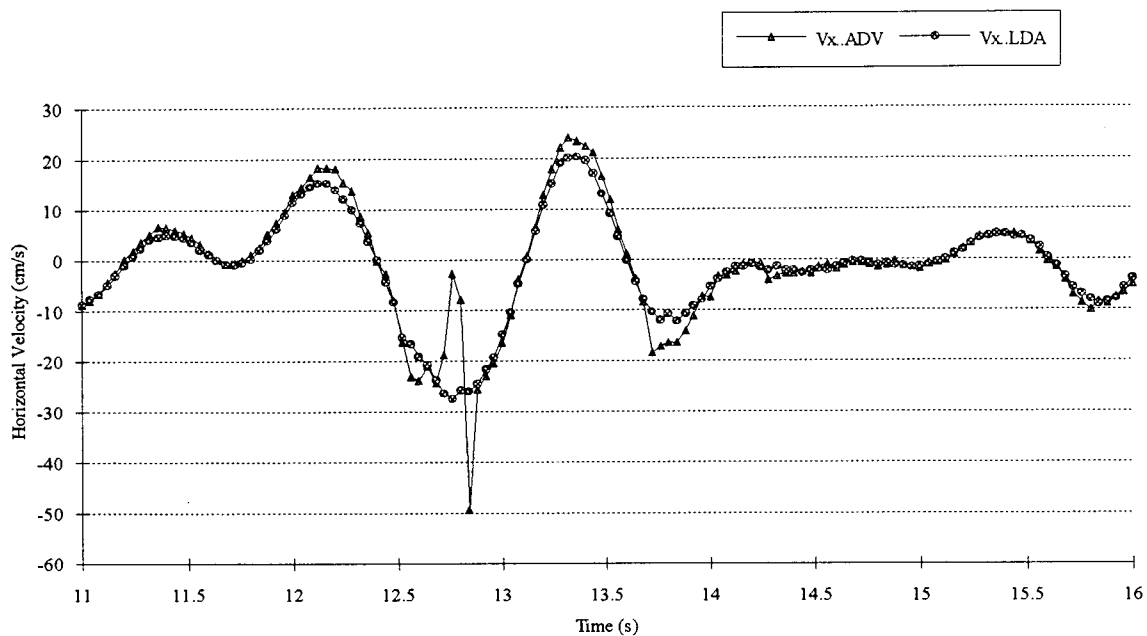
If the ADV-1 is measuring velocities of a large amplitude wave near the surface, there is a chance that the probe tip could come out of the water. For Figure 29, the probe tip is placed 6 cm below the SWL, and a 12 cm significant wave is generated. The ADV-1 probe comes out of the water at about 12.7 s and reenters the water at about 12.9 s. The ADV-1 recovers immediately and begins collecting data as designed, ensuring the amount of data lost is minimal.



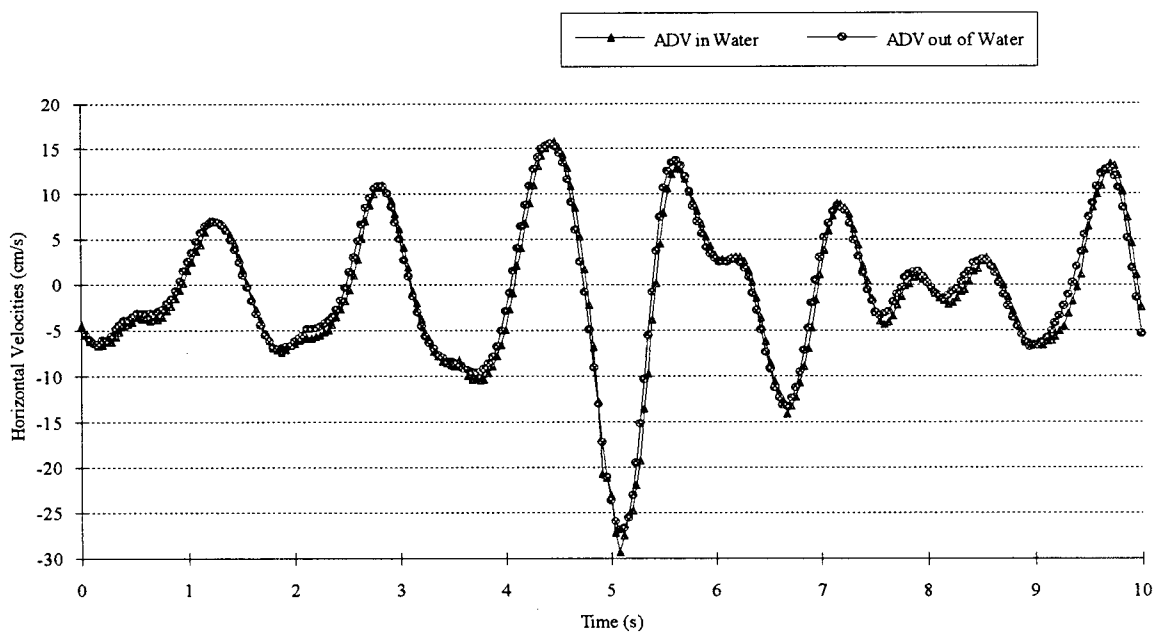
**Figure 28.** Transverse velocity of the 12 cm significant wave at a depth of 11 cm with an ADV-1 maximum velocity range of  $\pm 30$  cm/s.

The positioning of the ADV-1 sampling volume had to consider the turbulence the probe tip would produce. The 5 cm separation between the probe tip and the sampling volume was selected to prevent influence of the turbulence in the velocity measurements. Figure 30 shows the effect of the ADV-1 on the velocity measurement. First, the LDA measured the horizontal velocity of a 10 cm significant wave at the ADV-1 sampling volume, and then the ADV-1 was removed from the water, and the same wave was generated with the LDA measuring the orbital velocities. The ADV-1 probe tip does not have a noticeable effect on the horizontal velocity.

The ADV-1 and LDA velocity results are shown for several experiments. Stokes wave theory is used to compare experimental and theoretical results. The second-order Stokes wave theory is compared to experimental results for test 6, shown in Figure 20. The second-order Stokes theory is valid for this transitional wave, with a height of 3.8 cm in a water depth of 0.9 m, according to a wave theory regions chart in the Shore Protection Manual, Volume 1 (1984). The velocities under the second-order wave are



**Figure 29.** Plot of horizontal velocity the ADV-1 measures. Plot shows ADV-1 functioning as it moves in and out of the water.



**Figure 30.** Horizontal velocity of the LDA for a 10 cm significant wave.

$$u = \frac{H}{2} \frac{gk}{\sigma} \frac{\cosh k(h+z)}{\cosh kh} \cos(kx - \sigma t) + \frac{3}{16} \frac{H^2 \sigma k \cosh 2k(h+z)}{\sinh^4 kh} \cos 2(kx - \sigma t) \quad (9)$$

and

$$w = \frac{H}{2} \frac{gk}{\sigma} \frac{\sinh k(h+z)}{\cosh kh} \sin(kx - \sigma t) + \frac{3}{16} \frac{H^2 \sigma k \sinh 2k(h+z)}{\sinh^4 kh} \sin 2(kx - \sigma t) \quad (10)$$

where  $u$  is the horizontal particle velocity,  $w$  is the vertical particle velocity,  $H$  is the wave amplitude,  $k$  is the wave number,  $h$  is the water depth,  $z$  is the water depth of the particle,  $t$  is the particle time,  $g$  is gravitational acceleration,  $x$  is the position of the particle, and  $\sigma$  is the angular frequency (Dalrymple and Dean, 1992).

The generated regular wave has a height of 3.8 cm and a 2 s period. The water depth in the tank is 89.5 cm, and the velocities are measured 10.3 cm below the SWL. The velocity under the crest is evaluated. At this point,  $(kx - \sigma t)$  is equal to 0 and  $w$  equals 0. The horizontal particle velocity ( $u$ ) is 6.81 cm/s according to the Stokes second order theory. The ADV-1 measures 6.6 cm/s in the crest, and the LDA measures 5.7 cm/s in the crest for the horizontal velocity. Table 2 shows the average ADV-1 and LDA velocities under the crest for the regular waves in tests 3, 4, and 6, and the theoretical particle velocity under the crest using Stokes second order theory for each of these tests.

Test	ADV-1 Avg. Velocity under the Crest (cm/s)	LDA Avg. Velocity under the Crest (cm/s)	Stokes 2nd Order Vel. under the Crest (cm/s)
3	18.8	15.5	20.0
4	2.23	1.89	2.49
6	6.63	5.67	6.81

**Table 2.** Comparison of ADV-1 and LDA velocities under the crest with the theoretical values of Stokes second order.

Table 3 shows the results of the ADV-1 and LDA comparison tests.

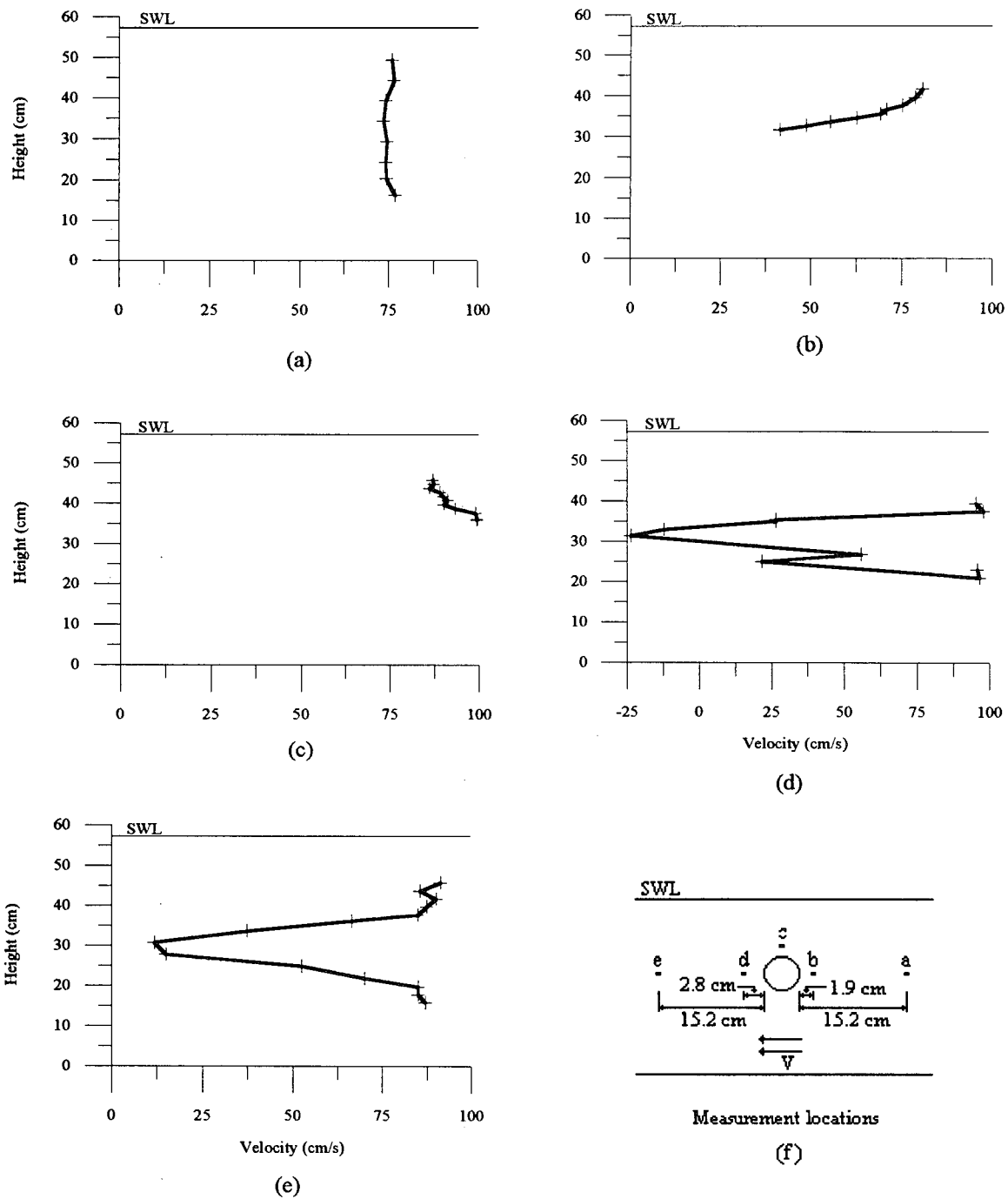
Test	Wave Period (s)	Wave Height (cm)	Max Vel Range (cm/s)	ADV-1 & LDA Vel Diff. (cm/s)
3	0.85	10	$\pm 30$	1.84
4	2	1.4	$\pm 3$	0.15
6	2	3.8	$\pm 10$	0.66
7	—	10 cm sig. wave	$\pm 30$	0.85
9	—	12 cm sig. wave	$\pm 30$	1.0

**Table 3.** Summary of ADV-1 and LDA comparison tests.

### **Velocity Profiles Around a Cylinder**

The ADV-1 can measure 3-D velocities in various laboratory settings. The ability of the ADV-1 to measure wave velocities and velocity profiles is only part of this instrument's capabilities. This instrument is also capable of measuring velocities around a structure. To demonstrate this a cylinder is placed horizontally across the width of a wave flume.

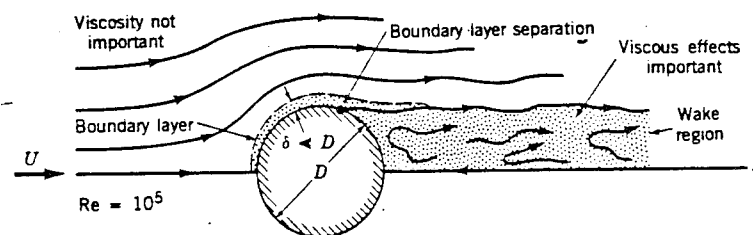
First, an 8.6 cm (3.4 in) cylinder is placed in the wave flume with a water depth of 57.2 cm (22.5 in). The cylinder center is 25.8 cm (10.1 in) below the SWL. Figure 31 shows the location of each velocity profile measurement in the flow field around the cylinder. The flow is nearly uniform in Figure 31(a). As the flow approaches the cylinder, Figure 31(b), the horizontal velocity immediately in front of the cylinder is significantly slower, and the velocity increases directly above that point. Above the cylinder, Figure 31(c), the velocity is greatest closer to the cylinder, and the velocity decreases as the distance from the top of the cylinder increases. The ADV-1 measured a velocity 2 to 3 mm from the top of the cylinder. This is closer to the boundary than the minimum distance suggested in the design specifications. The point of measurement in Figure 31(d) is 2.8 cm (1.1 in) behind the cylinder. As expected, the velocity slows behind the cylinder. Several points behind the cylinder have an average negative velocity. This is a result of vortices produced by the turbulence in the wake. The Reynolds number for this



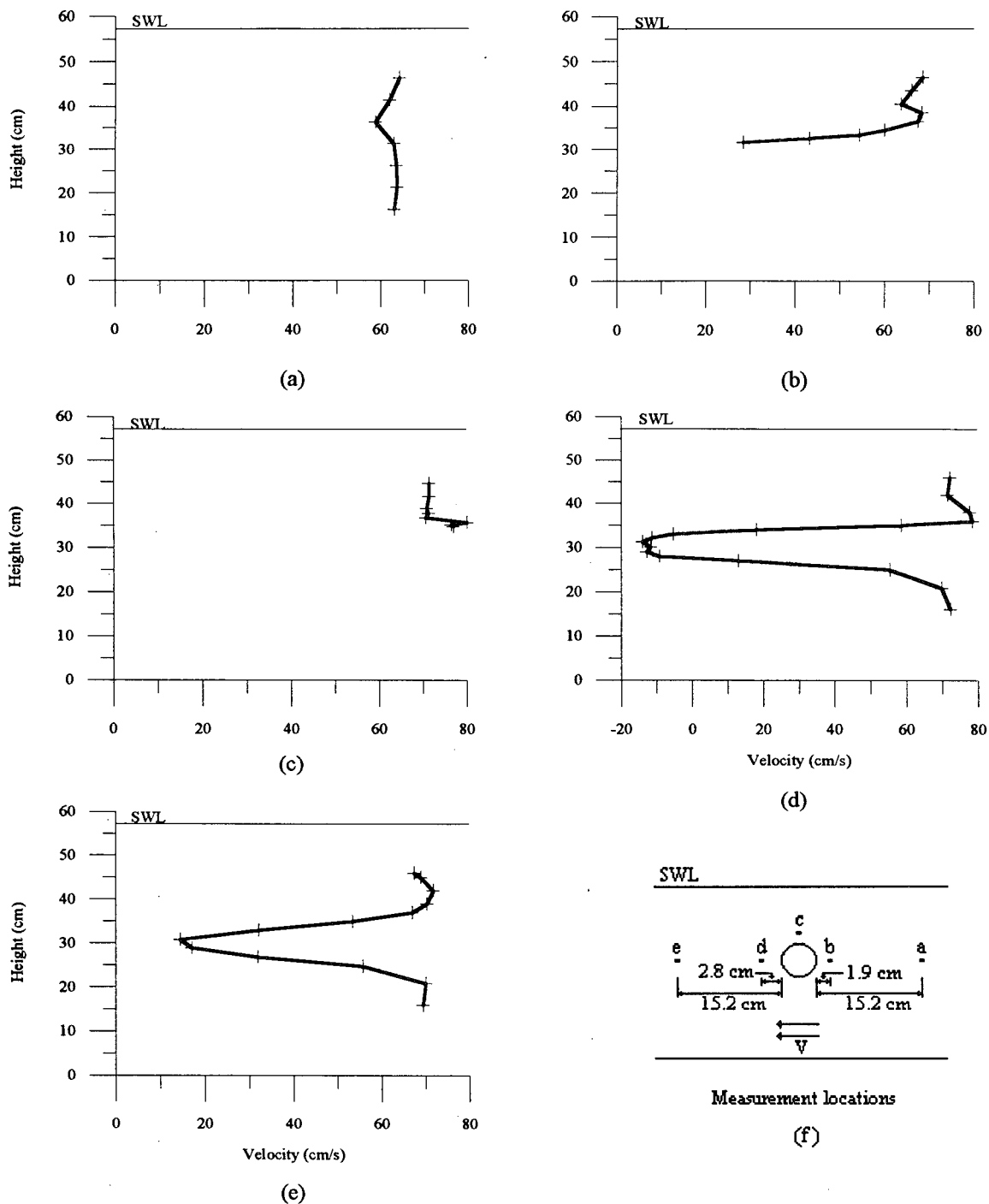
**Figure 31.** Velocity profile (a) 15.2 cm in front, (b) 1.9 cm in front, (c) above, (d) 2.8 cm behind, and (e) 15.2 cm behind an 8.62 cm circular cylinder in a wave flume with a water depth of 57.2 cm. Schematic (f) shows the measurement locations.

flow is  $7.58 \times 10^4$ . For  $300 \leq Re < 3 \times 10^5$ , the vortex street is fully turbulent. Figure 31(e) is 15.2 cm (6 in) behind the cylinder. The velocity in the wake is noticeably slower. This flow behind the cylinder compares to Figure 32 which shows the character of the steady, viscous flow past a circular cylinder in a large Reynolds number flow,  $Re$  equals  $10^5$  (Munson, Okiishi, and Young, 1990).

A smaller cylinder with an outside diameter of 6.1 cm (2.4 in) is placed in the wave flume 25.8 cm from the SWL. The water depth remains at 57.2 cm (22.5 in). Figure 33 shows velocity profiles in the flow field around the cylinder. The nearly uniform profile in Figure 33(a) is 15.2 cm (6 in) in front of the cylinder. Figure 33(b) shows the velocity profile 1.9 cm (0.75 in) in front of the cylinder. The velocity is lowest directly in front of the cylinder where separation of the flow is beginning. Velocities increase above this point. Above the cylinder, Figure 33(c), the velocity increases slightly near the surface and then decreases, as the distance from the cylinder increases, to a point, and the profile then remains uniform. The ADV-1 again measures a velocity 2 to 3 mm from the surface of the cylinder. Figure 33(d) shows the profile 2.8 cm (1.1 in) behind the cylinder. The negative average velocities in this profile are a result of the vortices produced by the turbulence. The Reynolds number for this flow around the cylinder is  $4.46 \times 10^4$ , and this flow also compares to Figure 32. This is within the region where the vortex street is fully turbulent. As expected, the velocity profile in the cylinder's wake, Figure 33(e), is slower closer to the cylinder's centerline.



**Figure 32.** Character of the steady, viscous flow past a circular cylinder in a large Reynolds number flow (Munson, Okiishi, and Young, 1990)



**Figure 33.** Velocity profile (a) 15.2 cm in front, (b) 1.9 cm in front, (c) above, (d) 2.8 cm behind, and (e) 15.2 cm behind a 6.1 cm circular cylinder in a wave flume with a water depth of 57.2 cm. Schematic (f) shows the measurement locations.



To explain more about the flow behind the cylinder, Figure 34 is a plot of the velocity measurement 2.8 cm (1.1 in) behind the 6.1 cm (2.4 in) cylinder. The ADV-1 sampling volume is along the horizontal centerline of the cylinder. Figure 34 shows the velocity fluctuations of the vortices immediately behind the cylinder.

Potential flow theory is commonly used to describe the flow around a body. This theory is useful for predicting the horizontal velocities on top of the 8.6 and 6.1 cm cylinders. Potential flow theory assumes the flow is uniform. The stream function for flow around a cylinder is

$$\psi = Ur \left(1 - \frac{a^2}{r^2}\right) \sin \theta \quad (11)$$

and the corresponding velocity potential is

$$\phi = Ur \left(1 + \frac{a^2}{r^2}\right) \cos \theta \quad (12)$$

where  $U$  is the uniform velocity,  $a$  is the outside radius of the cylinder,  $r$  is the distance from the center of the cylinder to a point in the flow field, and  $\theta$  is the angle from the horizontal streamline.

The velocity components from Equations 10 and 11 are

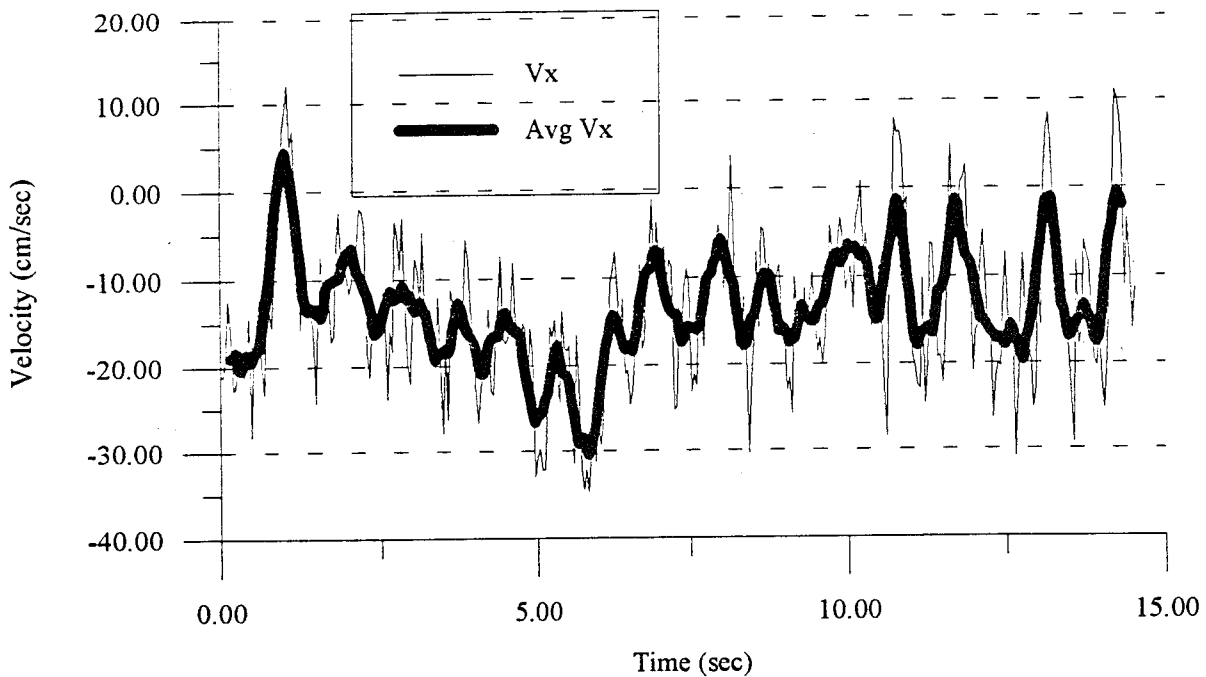
$$v_r = \frac{\partial \phi}{\partial r} = \frac{1}{r} \frac{\partial \psi}{\partial \theta} = U \left(1 - \frac{a^2}{r^2}\right) \cos \theta \quad (13)$$

and

$$v_\theta = \frac{1}{r} \frac{\partial \phi}{\partial \theta} = -\frac{\partial \psi}{\partial r} = -U \left(1 + \frac{a^2}{r^2}\right) \sin \theta \quad (14)$$

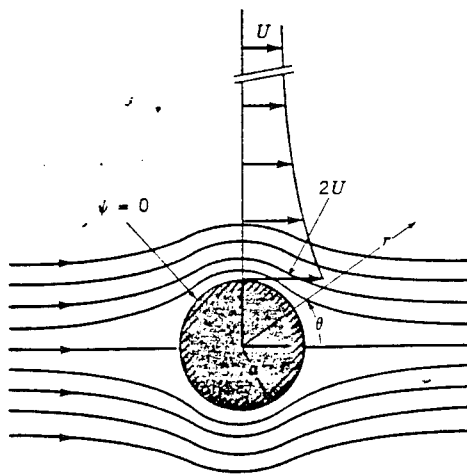
where  $v_r$  is the velocity perpendicular to the cylinder and  $v_\theta$  is tangential velocity to the cylinder.

On the surface of the cylinder,  $r$  equals  $a$  and  $v_r$  equals 0 (Munson, Okiishi, and Young, 1990).



**Figure 34.** Velocity measurement 2.8 cm behind the 6.1 cm cylinder. The ADV-1 sampling volume is along the horizontal centerline of the cylinder.

A sketch of the streamlines for the flow field represented by Equations 11 and 12 is shown Figure 35.



**Figure 35.** The flow around a circular cylinder (Munson, Okiishi, and Young, 1990)

The potential flow theory is used to predict horizontal velocities,  $v_\theta$ , on top of the cylinder.

For the 8.6 cm (3.4 in) cylinder,  $v_\theta$  is compared to the experimental velocities,  $V_x$ , in Table 4.

The theoretical velocities,  $v_\theta$ , of the 6.1 cm (2.4 in) cylinder are compared to the experimental velocities,  $V_x$ , in Table 5.

$r$ (cm)	$v_\theta$ (cm/s)	$V_x$ (cm/s)
4.61	140.5	99.3
5.21	126.3	99.4
6.45	108.5	98.9
7.31	101.0	93.4
8.61	93.8	90.1
9.65	90.0	91.1
10.31	88.1	89.9
12.65	83.7	86.0

**Table 4.** Theoretical,  $v_\theta$ , and experimental,  $V_x$ , horizontal velocities at a distance  $r$  above the center of the 8.6 cm (3.4 in) cylinder.

$r$ (cm)	$v_\theta$ (cm/s)	$V_x$ (cm/s)
3.34	114.5	77.0
3.74	104.0	76.4
4.24	94.8	80.0
5.26	83.5	70.6
6.35	76.9	71.2
7.43	73.1	70.9
10.23	68.1	71.4
13.23	65.9	71.4

**Table 5.** Theoretical,  $v_\theta$ , and experimental,  $V_x$ , horizontal velocities at a distance  $r$  above the center of the 6.1 cm (2.4 in) cylinder.

The theoretical and experimental velocities, in Tables 4 and 5, have a greater difference near the cylinder. As the distance above the cylinder increases, the difference between the theoretical and experimental values substantially decreases. The ADV-1 is not capable of measuring inside the boundary layer on small cylinders.

## CHAPTER 5

### CONCLUSIONS

The Acoustic Doppler Velocimeter (ADV-1) is capable of measuring current velocities in various laboratory settings. Operation of the ADV-1 is relatively simple compared to the effort and knowledge required to operate the laser Doppler anemometer. Since the ADV-1 system software, described in Appendix A, is extremely user friendly, the effort of the user is minimal. The user only has to enter the water temperature and select a velocity range and sampling rate to begin collecting velocity data. The most difficult portion of the operation is the mounting of the ADV-1 probe in the laboratory wave tanks and flumes.

The ADV-1 was initially calibrated by the manufacturer. To verify this calibration, a test was performed by mounting the ADV-1 on a motorized tow carriage. The carriage velocities and the measured ADV-1 velocities were compared. The statistical uncertainty of the measurements within a  $\pm 30$  cm/s range was 1.7 mm/s, and the uncertainty within a  $\pm 100$  cm/s range was 3.92 mm/s.

The ADV-1 was successfully tested in a variety of laboratory settings involving oscillatory flow and uniform flow. The ADV-1 measured the three velocity components of the waves in the wave tank while the LDA only measured the horizontal and vertical velocity components. The ADV-1 horizontal velocity average was 0.90 cm/s higher than the LDA horizontal velocity average, and the ADV-1 vertical velocity average was 0.93 cm/s lower than the LDA. A maximum SNR of 22 dB was obtained. This is sufficient, however, a higher SNR would produce better quality velocity data. Data obtained with a SNR of 18 dB had significantly higher variations than the data obtained with a SNR of at least 20 dB. To obtain a higher SNR, more seeding material would be required and this would adversely affect the laser back scatter. The maximum velocity range also had an effect on the data quality. To ensure valid data, measured current velocities cannot exceed the selected maximum velocity range, but the velocity range

should not be set too high. If the range is too high, then the velocity data will also have large variations. The maximum velocity range should be set at the lowest possible level so that all measured velocity data are within the range. The ADV-1 probe came out of the water during several of the wave experiments. The location where the ADV-1 came out of the water has several large velocity spikes. When the probe reentered the water, the ADV-1 immediately began collecting velocity data. This feature of the ADV-1 ensures that there is minimal interruption if the instrument does come out of the water.

In the variable slope wave flume, the velocities measured by the pitot tube and ADV-1 in a horizontal velocity profile had a 3.5 % difference. The ADV-1 profile when compared to the Vanoni approximation distribution in an open channel had only a 2.5 % difference, and the pitot tube profile had a 3.8 % difference with the Vanoni profile velocities. The ADV-1 is capable of measuring velocity profiles from the bottom of a tank or flume to point a 5 to 6 cm from the surface. The water depth must be low enough to ensure the ADV-1 cylindrical housing is not submerged. When the housing is submerged, the increased drag causes substantial vibrations which affect the quality of the data.

The ADV-1 is capable of measuring velocity profiles in the flow field around a cylinder. However, the velocity of the fluid within 3 mm of the cylinder surface cannot be measured by the ADV-1. Thus for small cylinders, it was not possible to measure inside the boundary layer. With the three-dimensional probe, the ADV-1 is restricted from making valuable velocity measurements around the cylinder (i.e. underneath the cylinder) without submerging it.

The operation of the ADV-1 has several steps to follow to assure the best possible velocity data is obtained. To assist a user with this operation, an operational manual was developed from these tests. The manual is located in Appendix A. Appendix B shows a suggested mounting device for the ADV-1. At a minimum, the mounting device should have measuring scale to show the location of the probe tip in the water column, and a screw-mechanism for raising and lowering the instrument. This mounting device attaches to the top of the tank.

The ADV-1 is a rugged instrument which can be easily relocated to measure three-dimensional components of water velocity in various laboratory facilities. The complete ADV-1 system, including extensive operation interface and data collection software, costs approximately \$10,000. A mounting and traversing system for the ADV-1 would cost approximately \$5000.

Additional probe stems are available from SonTek, Inc. A 3-D up-looking probe, for measuring orbital velocities in the wave crest or 3-D velocities near the surface for uniform flow, and a 2-D side-looking probe, for measuring velocities near structures/walls or near the surface, can be purchased for approximately \$6000, each costing \$3000. The additional probes would substantially improve the research capabilities of Texas A&M University.

## REFERENCES

- DALRYMPLE, R.A. & DEAN, R.G. 1992 *Advanced Series on Ocean Engineering, Volume 2-Water Wave Mechanics for Engineers and Scientists*. World Scientific Publishing Co. Pte. Ltd., River Edge, NJ.
- DAUGHERTY, R.L., FRANZINI, J.B., & FINNEMORE, E.J. 1985 *Fluid Mechanics with Engineering Applications*. McGraw-Hill, Inc., New York, NY.
- GOLSTEIN, R.J. 1983 *Fluid Mechanics Measurements*. Hemisphere Publishing Corporation, New York, NY.
- KRAUS, N.C. 1993 LABFLOW Report. Unpublished. Coastal Engineering Research Center, Vicksburg, MS.
- HUGHES, S.A. 1994 Personal Communication: ADVView Document. Coastal Engineering Research Center, Vicksburg, MS.
- MUNSON, B.R., YOUNG, D.F., & OKIISHI, T.H. 1990 *Fundamentals of Fluid Mechanics*. John, Wiley & Sons, Inc., New York, NY.
- PRISLIN, I. 1993 Personal Communication. Texas A&M University, College Station, TX.
- SONTEK. 1993 ADV-1 Installation and Operation. *Technical Reference Manual*. SonTek, Inc., San Diego, CA.
- SPELL, C.A. 1992 Modulation and kinematics of mechanically-generated short gravity waves riding on long waves. *Thesis for Masters of Science*. Texas A&M University, College Station, TX.
- U.S. ARMY CORPS OF ENGINEERS. 1984 *Shore Protection Manual, Volume I*. Fourth Edition. Coastal Engineering Research Center, Vicksburg, MS.
- URICK, R. J. 1983 *Principles of Underwater Sound*. McGraw-Hill, Inc., New York, NY.
- VANONI, V.A. 1941 Velocity distribution in open channels. *Civil Eng.*, vol 11, 356 - 357.

## APPENDIX 1

### ACOUSTIC DOPPLER VELOCIMETER (ADV-1) OPERATIONS MANUAL

#### EQUIPMENT

The ADV-1 system consists of the two primary parts, the ADV-1 probe and the personal computer which has the ADV-1 software. The ADV-1 probe cable connects to a signal processing card installed in the PC ( This cable should only be connected and disconnected when the computer is turned off ). This system requires a 33-MHz 386 or 486DX personal computer with 640 k RAM, hard disk and color VGA graphics. The PC should have one 16-bit slot in the IO expansion bus available for the signal processing card. The current set-up uses a 33-MHz 386DX PC. The ADV-1 Data Acquisition Program is installed in the E:\ drive under the "ADV-1" directory. This program is accessed by typing "ADV" at the DOS prompt. The details of the software are discussed in the ADV-1 SOFTWARE section.

The ADV-1 probe measures the  $u$ ,  $v$ , and  $w$  velocity components. The velocities are measured in the sampling volume which is centered 5 cm below the probe tip. This volume is a disk, 3 mm high and 6 mm wide. The ADV-1 design requires a minimum of 5 mm between the sampling volume and boundary for data collection. For smooth surfaces, the ADV-1 may obtain an accurate velocity reading closer than 5 mm. The exact position of the probe from the nearest boundary is shown in the data acquisition software. The probe must be mounted with all three receiver arms in the water to ensure proper operation. The painted receiver arm on the probe points in the direction of the  $x$ -axis. The  $y$ -axis and  $z$ -axis are defined as a right-hand coordinate system with  $z$  pointing upward. The probe should always be rinsed in fresh water if used in salt water.

#### SEEDING

This instrument operates on the Doppler principle. A short acoustic pulse of known frequency is transmitted along a vertical axis. The echo from the water is received in the three



transducer elements and analyzed for frequency in the processing board. The frequency shift between the transmit pulse and the received echo is proportional to the water velocity. The echo must be strong enough to allow proper calculation of the frequency shift. A weak echo will have statistically noisy data.

The strength of the echo is quantified by the "signal-to-noise ratio" (SNR). The SNR is expressed in terms of decibels (dB). SonTek recommends a SNR consistently above 20 dB when collecting raw data at 25 Hz. For mean data, sampling at 10 Hz, a SNR of 5 dB is recommended. This scattering strength depends on the concentration and size of the particles suspended in the water. The particles can be naturally occurring suspended sediments, bubbles entrained with pump systems, or artificial "seeding".

SonTek recommends seeding stagnant, clear bodies of water with hollow spheres that have a density close to that of water and a size around 10  $\mu\text{m}$ . This particle size generates a relatively strong echo per unit of concentration. The smaller particles used to seed Laser Doppler systems, typically 1  $\mu\text{m}$ , are not recommended for the ADV-1. The recommended seeding level for the material purchased from SonTek is 10-50 grams per cubic meter or an ounce per ton. This material does not have adverse effects on the performance of Laser Doppler systems. If a low SNR reading is observed after seeding, the user should clean the transmit and receive transducers. This can be accomplished by gently rubbing the transducers with a finger.

### **ADV-1 SOFTWARE**

The real-time data acquisition program has two modes of operation, the Setup Mode and the Data Acquisition Mode. By typing "ADV" and pressing "ENTER" at the DOS prompt, the program enters the Setup Mode. In this mode, the user specifies a number of parameters which are necessary for the operation of the ADV-1. After selecting the required parameters, the program is taken into the Data Acquisition Mode by selecting the corresponding item in the Setup menu. In the Data Acquisition Mode, the program continuously collects, displays and records velocity data until it is interrupted by the user.

### Setup Mode:

The items listed below, with their descriptions, are in the setup menu. The operator can move through the items by using the up/down, or page up/ page down, keys. The highlighted item can be executed/changed by pressing the enter key, or by using the left/right keys if it is a multi-choice item. If the program prompts the user for an input after accidentally pressing the enter key, the user can recover by pressing the escape key.

- a. *Units system*: Permits selection of units as Metric or English
- b. *Water Temperature*: This is required for calculating the speed of sound. Temperature can be entered in °C or °F, depending on which system is selected.
- c. *Water Salinity*: This is also required to calculate the speed of sound. Salinity is always entered in parts per thousand (ppt).
- d. *Speed of Sound*: The speed is computed from the values of temperature and salinity. This item cannot be changed by the user.
- e. *Sampling Rate*: The value must be entered. The maximum sampling rate is 25 Hz.
- f. *Velocity Range*: This item permits selection of the appropriate maximum velocity range of  $\pm 3, 10, 30, 100, \text{ or } 250 \text{ cm/s}$ . These ranges refer to the maximum horizontal velocity. The measured vertical velocities should not be greater than one-third of the selected maximum velocity range.
- g. *External Synchronization*: This is a digital sync input on the signal processing module (computer board) so ADV-1 measurements can be synchronized with those of other instruments. This can be "DISABLED" when not in use.
- h. *Record to file*: This item permits assignment of a filename for recording the velocity data. Checks are incorporated into this item to ensure that a valid filename is given and that an existing file is not accidentally written. If a filename is not entered, the system will still operate, but the data will not be collected.
- g. *File Comment*: These items permit the user to enter up to three 60 character lines of text which will be included in the data file for the purpose of documenting the data.
- h. *START Data Acquisition*: If setup is satisfactory, data acquisition is started by pressing "ENTER".

- i. *EXIT*: By pressing "ENTER" on this item, the program will terminate and return to DOS.

#### Data Acquisition Mode:

The first screen in this mode displays the distance of the probe tip to the nearest boundary, the distance of the sampling volume to the nearest boundary, and the maximum velocity range. This second feature is useful when positioning the ADV-1 for measuring velocities near a boundary. If the sampling volume is more than 25 cm from a boundary, these items will not display a distance. From this screen, data acquisition is started by pressing the F10 key.

This screen is divided in three sections. The top of the screen displays information on the current status of data acquisition as well as the exact values of the last data sample. The middle portion of the screen presents a real-time trace of the three velocity components. The bottom of the screen indicates which menu keys are active during data acquisition and their functions. These keys may be used during data collection. Using these keys will not affect data collection or recording. The status portion of the screen is updated after a sample is collected but not more often than once a second. The items listed below are on the data acquisition screen.

- a. *Recording File*: This displays the name of the file to which data are being recorded. If the user is not recording, the words "NOT RECORDING" are displayed.
- b. *File Size/Disk Space/Recording Time Left*: These fields will display information only if recording is enabled. File Size displays the current size of the data file in kilobytes. Disk Space gives the amount of space left on the disk where the data file resides. Recording Time Left tells the user how many hours of data can be collected at the present rate before the disk is exhausted.
- c. *Start Time/Current Time*: These times are obtained from the DOS time function in the computer. The Start Time is the time at which data acquisition was started. Current time is the time of the last screen update, which is updated every second.
- d. *Test Time*: This is the total length, in seconds, of the time series of the collected velocities. This time is derived from the ADV-1's highly accurate clock rather than from the PC clock.
- e. *Sample Number*: This is the number of the last velocity sample displayed. The first velocity sample collected by the ADV-1 is numbered "1".

- f. *Vx/Vy/Vz*: These are the exact values of the last velocity sample in the units corresponding to the Units System selected in the setup mode.
- g. *SNR1/2/3*: These are the signal-to-noise ratio measured at each of the three receivers in the ADV-1 during the last displayed sample. The values are given in dB relative to noise level. The ADV-1 requires a SNR of at least 20 dB for best performance.
- h. *Std Vx/Vy/Vz*: These are the standard deviations of each velocity component.
- i. *Real-time Velocity Trace*: This plot shows a graphics display of the most recent velocity sample. Continuous time series of the three velocity components are plotted left to right versus time. The most recent point is identified by a vertical bar. Once plot has reached the right side, plotting resumes on the left side. This feature allows the user to view a length of time series equal to the full time span of the plot at all times.
- j. *F1 - Display Probe*: This item shows which probe is in use, 0 to 3.
- k. *F3 - Change Time Span*: Pressing the F3 key permits the user to change the span of the real-time trace. A change will reset the trace.
- l. *F5 - Change Velocity Scale*: Pressing the F5 key permits the user to change the full velocity scale of the trace. A change will reset the trace.
- m. *F7 - Mark Data Point*: Pressing the F9 key marks the current data sample. On the real-time trace, this mark is shown as a vertical bar.
- n. *F9 - Reset Trace*: Pressing the F7 key resets the real-time trace by erasing the current traces and beginning a new plot from the left side.
- o. *Space Bar - Pause Display*: Pressing the space bar freezes the screen display. The updated display is resumed by pressing the space bar again. After the pause, the discontinuity in the traces appears since the data collected during the pause are lost to the display. During the pause, the program is still collecting and recording data without interruption.
- p. *[ALT] F10 - Stop Program*: The user initiates the termination of the program by pressing the ALT and F10 keys simultaneously. The user is then presented with a prompt, Yes/No multi-choice window, to confirm the intention to stop the program. Data collection continues until the confirmation is given.

This program records data into highly compressed binary files. After data acquisition is started, the program records a number of internal configuration parameters as well as the values of the items set by the user in the Setup menu. After each sample, the program records a binary

record containing velocity data, SNR data, and correlation data. All of the information contained in these data files can be accessed by data conversion programs within the ADV software.

### **ADV-1 Data Conversion Programs**

The programs GETCTL.EXE, GETVEL.EXE, and GETSNR.EXE extract the configuration and setup information, the time and velocity data, and the time and SNR data, respectively, from the ADV-1's data files and store them in tabular ASCII files suitable for use with common analysis software such as LOTUS, QUATROPRO, GRAHPER, MATLAB, etc. This can be performed on any IBM PC-compatible computer. The process for using these data conversion programs is described below.

To use GETCTL.EXE, type "GETCTL {ADV data file} {output file}" at the DOS prompt. Both file names must be given without an extension. The program assumes that the ADV data file has extension .ADV, and the output file has extension .CTL. For example,

"GETCTL WAVES3 WAV3"

will extract the configuration information from ADV data file WAVES3.ADV and convert it to ASCII in file WAV3.CTL. Similarly, to use GETVEL or GETSNR, type

GETVEL {ADV data file} {output file} {first sample} {last sample}

GETSNR {ADV data file} {output file} {first sample} {last sample}

at the DOS prompt. The program will assign the ASCII files the extensions .VEL and .SNR, respectively. These lines also show the capability of the program to permit the user to extract only portions of the data. If last sample is larger than the actual number of samples in the file, the program will simply stop after the last sample in the file is extracted. For example,

"GETVEL WAVES3 WAV3 100 199"

will extract the velocities for samples 100 through 199 from the ADV data file WAVES3.ADV and convert them to ASCII in file WAV3.VEL.

The programs GETVEL and GETSNR generate ASCII files with one line per sample. The first value in each line is the sample time, in seconds, from the start of data acquisition. The last

three values correspond to  $V_x$ ,  $V_y$ , and  $V_z$ , or SNR for beams 1, 2, and 3. The units for velocity correspond to the units system used during data acquisition, either cm/s or ft/s. The units for SNR are dB relative to the noise level. The second value in each line is the event flag which is always "0" unless the data sample was marked during data acquisition. The first marked sample in the file has an event flag value of 1, the second a value of 2, etc.

Hughes (1994) also has a program, ADView, which allows the user to enter the original ADV file (i.e. data file.ADV) to extract the data. His program utilizes the GETCTL.EXE and GETVEL.EXE data conversion programs. The ADView program is installed within the E:\ADV directory and is accessed by typing "ADVIEW" at the DOS prompt. The program then asks for the name of the input data file. By typing DATAFILE.ADV, ADView extracts from the binary file the ASCII files containing the configuration information and the velocity data. The user can now view a plot of each velocity component time series, zoom in on any portion of the plot and make hard copy prints of the current screen plot.

## APPENDIX 2

### SUGGESTED ADV-1 MOUNTING DEVICE

This ADV-1 mounting device shown below can be used in the laboratory wave tank and variable slope wave flume. The ADV-1 would be mounted inside the two horizontal bars. These horizontal bars should form around the ADV-1's cylindrical housing and have foam/rubber inside the bars. These bars should be able to hold the ADV-1 securely and move along the vertical support bars. The horizontal bars should attach to the gear system. This gear system should have a single screw device to allow the user to move the ADV-1 vertically. The support bars should be circular and strong enough to provide stable support. The support bars can be attached to another bar for attachment to the tank or flume. The support bar on the side of the gear system should be marked with a metric ruler and have a rack on one side for the gear system.

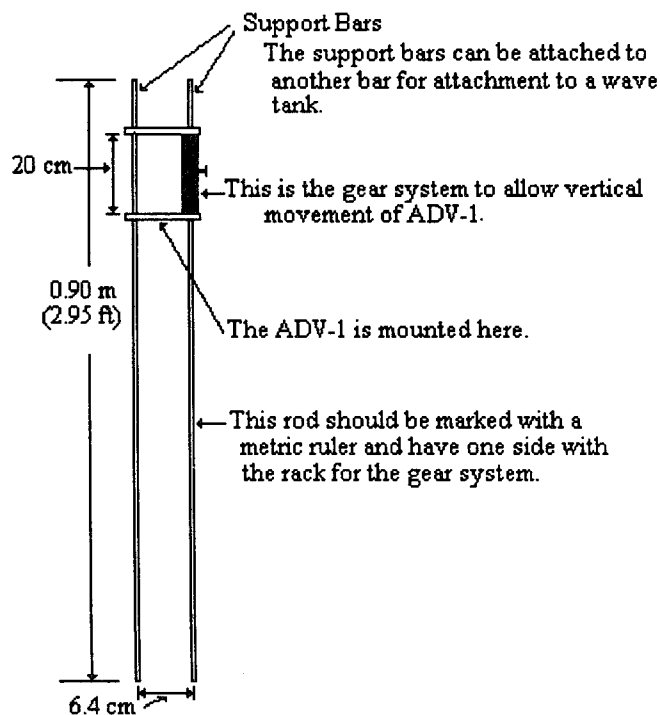


Figure 36. Suggested mounting device for the ADV-1.